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DEVELOPMENT OF ALUMINUM CASTINGS WITH HIGH IMPACT STRENGTH AT LOW TEMPERATURES

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Prepared under Contract No. NAS 8-1689 *by*
BATTELLE MEMORIAL INSTITUTE
Columbus, Ohio
for

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INTRODUCTION

This report describes the results obtained during the second year of a 2-year investigation of methods of improving the impact properties at low temperatures of aluminum-alloy sand castings. The research described in this report was carried out in the period between June 26, 1962, and June 26, 1963. The program was terminated at the end of this research period.

This program was initiated to determine whether high-strength aluminum castings could be developed which would show impact properties at low temperatures significantly better than those of present-day aluminum castings. Present space-vehicle technology has resulted in considerable interest in complex aluminum-alloy components for use at very low temperatures. Because of the relatively small number of components of a specific configuration required, the use of sand castings is economically quite advantageous.

SUMMARY OF PRIOR WORK

The basic approach followed in this program was to determine whether increased alloy purity would permit aluminum castings to be made showing tensile properties comparable with those of existing commercial aluminum castings, but also showing superior impact properties at low temperatures. Aluminum has a low solid solubility for a number of its common impurity and alloying elements. As a result, aluminum castings commonly contain a significant quantity of intermetallic phases which can act as internal notches to lower the impact properties. Such phases would be particularly damaging at low temperatures and high strain rates. Therefore, increased alloy purity and a careful control of alloy additions should result in much lower intermetallic content and improved impact properties at low temperatures. It was also considered possible that certain of the common alloying additions might lower the intrinsic impact properties of aluminum when present in solid solution. Such an effect might result from microsegregation at grain boundaries or from an inhibiting effect on deformation characteristics at high strain rates. The validity of this approach was examined during the first year of this investigation.(1)*

After a study of the literature on the low-temperature properties of aluminum castings, five alloy compositions were selected for an examination of the effect of alloy purity on the properties of aluminum castings:

*References listed at end of report.

A356	7.0Si-0.3Mg
355	5.0Si-1.3Cu-0.5Mg
195	4.5Cu-0.8Si
A612	6.5Zn-0.7Mg-0.5Cu
220	10.0Mg

These alloy compositions represented the major types of aluminum sand castings. Each of these compositions was prepared on both a commercial-purity and a super-purity (99.99 per cent aluminum) base and cast into core-sand molds to obtain material for evaluation. Specially prepared super-purity master alloys and carefully controlled melting procedures were used to minimize contamination. After heat treatment, the properties of the ten castings were compared. The results of this comparison are summarized in Table 1.

It is apparent from the data in Table 1 that increased alloy purity significantly increased the low-temperature impact properties of A356-T6, 355-T6, 195-T6, and A612-T6, but that it had little effect on 220-T4 and A612-F. The highest impact properties at low temperature were observed in A612-T6 and 195-T6. It was concluded that increased alloy purity had a marked ability to improve low-temperature impact properties, and that alloying additions also were of significance. Since the 220-T4 castings showed a noticeable loss of impact strength as temperature decreased, while the impact properties of A612 were much superior in the T6 as compared to the F temper, it appeared that magnesium in solid solution might be detrimental to low-temperature impact properties.

From microstructural studies, it was apparent that one of the principal effects of high purity was to eliminate the iron intermetallic phase which is present in large amounts in commercial-purity castings. This intermetallic tends to form as rather massive irregular particles in the cast grain boundaries and apparently is very damaging to impact toughness.

In a limited follow-up study, the effect of silicon in 195-T6 castings was examined in more detail. It was found that a binary Al-Cu alloy developed much higher impact properties than did 195-T6. At -320 F, the Charpy impact properties of the high-purity binary alloy casting were 14.0 ft-lb as compared with 8.0 ft-lb for high-purity 195-T6. A high-purity Al-Cu-Si casting containing 3.0Si showed Charpy impact properties at -320 F of only 2.3 ft-lb. These results, in conjunction with the results reported in Table 1 for A356 and 355, suggested that silicon may be undesirable in amounts above 1 per cent where silicon is present as a separate phase in aluminum casting alloys.

The research conducted during the first year confirmed that the low-temperature impact properties of aluminum sand castings could be significantly improved by increased alloy purity. It was also concluded that an aluminum sand-casting alloy for low-temperature use should be based on either the Al-Cu or the Al-Zn-Mg system.

COMPLETION OF STUDIES IN PROGRESS

At the completion of the first year of work on this program several small programs were under way which were not sufficiently advanced for the results to be included in the

TABLE 1. EFFECT OF PURITY AND COMPOSITION ON THE PROPERTIES OF ALUMINUM CASTINGS[a]

		Unnotched Tensile Properties at 75 F			Charpy Impact Properties, ft-lb			Notched: Unnotched Strength Ratio[c],
Alloy and Temper	Purity	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	75 F	-320 F	-450 F	-320 F
195-T6	Commercial	44.2	24.4	8.2	2.0	2.0	2.0	1.05
	High	48.3	33.8	6.3	8.4	8.0	7.6	1.42
A356-T6	Commercial	37.3	24.4	7.5	2.8	2.0	2.4	1.14
	High	37.4	23.5	12.4	5.0	5.0	5.2	1.22
355-T6	Commercial	42.3	29.4	5.2	1.0	1.0	1.0	0.92
	High	40.4	24.4	9.3	3.8	3.0	3.8	1.18
A612-F	Commercial	39.3	29.4	4.9	3.6	2.4	2.2	1.23
	High	37.1	32.7	1.8	2.0	2.0	1.2	1.05
A612-T6[b]	Commercial	39.2	30.3	8.5	7.1	8.4	--	--
	High	48.6	43.5	10.2	10.6	14.3	--	--
220-T4	Commercial	46.7	29.8	9.5	5.6	1.0	1.0	1.04
	High	62.4	34.4	24.5	5.2	1.0	1.2	1.02

(a) As measured on bars machined from a sand-cast double-leg keel block.
(b) A612 alloy was examined in the T6 temper, as well as in the F temper in an abbreviated study.
(c) Stress Concentration Factor (K_t) of 6.

1962 Summary Report.[1] These studies which supplement the results described in that report are described below.

Low-Temperature Properties of Al-Cu Alloys

The impact properties reported by NASA for -420 and -450 F tests on material from Alloys 14 through 16 appeared too high. A discussion of these tests with NASA personnel suggested that a false machine setting might have been used and that the values could be in error by a factor of two. The values were divided by two and reported in Table 18 of the Summary Report.[1] However, even after correction, they appeared unrealistic. Therefore it was decided to prepare additional impact samples from these three alloy castings.

Impact samples were machined from the heat-treated weld plates of Alloys 14 through 16 for additional tests at Battelle and NASA. The results of impact tests on these alloys are given in Table 2. It would appear that the original values were in error by a factor of four instead of two. The lower impact values obtained in the recheck of impact properties are probably related to a difference in section size during heat treatment. The original samples were heat treated as 1/2-inch-square blanks while the recheck samples were heat treated as 1-inch-thick plate.

Tensile samples machined from keel-block castings of three high-purity casting alloys were also submitted to NASA for testing at -420 F. The results of these tests (one sample for each alloy) are reported in Table 3 along with average tensile properties at 75 and -320 F as measured at Battelle. Alloy 12 (high-purity 195-T6) was somewhat less ductile at -420 F than at -320 or 75 F. The other two alloys were more ductile at -420 F. Since these are the results of a single test, not too much significance should be attached to them, except to note that the alloys are ductile and strong at -420 F.

Properties of 220-T6 Castings

Quite significant improvements were noted in A612 castings when the material was tested in the T6 rather than the F temper, as shown in Table 1. This suggested that the 220 castings, originally tested in the T4 temper, might benefit from a T6 heat treatment.

A limited amount of material was available from the keel-block castings of 220 alloy for re-examination of the effect of heat treatment on tensile and impact properties. Sample blanks in the T4 temper were re-heat treated to T4 to eliminate any room-temperature aging effects which may have developed since they were originally heat treated and then aged to a T6 temper. The heat-treatment schedule is outlined below:

Solution annealed 20 hours at 810 F and quenched in boiling, salt-saturated water (original treatment)
Solution annealed 1/2 hour at 810 F, quenched in boiling, salt-saturated water, and aged 4 hours at 300 F.

The results of mechanical property tests on this material are given in Table 4.

TABLE 2. RECHECK OF IMPACT PROPERTIES OF THREE ALLOYS

Test Temperature, F[a]	Charpy Impact Properties, ft-lb 1	2	3	4	5	Average	Original Test Results, ft-lb
			Alloy 14 (4.1Cu)				
75	6.2	9.5	9.0	10.0	7.8	8.5	10.1
-320	11.0	13.0	10.0	9.0	13.0	11.2	14.0
-420	8.0	12.0	11.0	11.0	13.0	11.0	47.6
-450	10.0	11.0	11.0	13.0	14.0	11.8	56.0
			Alloy 15 (3.7Cu-3.0Si)				
75	2.0	1.9	1.7	1.5	--	1.8	2.0
-320	1.6	1.2	1.5	2.0	1.9	1.6	2.3
-420	2.0	2.0	2.0	2.0	2.0	2.0	7.4
-450	1.0	2.0	1.0	1.0	1.0	1.2	8.0
			Alloy 16 (4.4Cu-0.3Mn-0.1V-0.1Ti)				
75	6.9	5.6	5.0	5.7	2.0[b]	5.8	5.6
-320	6.1	6.8	7.0	6.0	1.5[b]	6.5	7.9
-420	7.0	6.0	7.0	6.0	6.0	6.4	32.6
-450	8.0	6.0	6.0	6.0	5.0	5.8	36.2

(a) Tests at -420 and -450 F run by NASA.

(b) Omitted in average.

TABLE 3. TENSILE PROPERTIES OF ALUMINUM CASTING ALLOYS

Test Temperature F	Unnotched Tensile Properties: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent
	Alloy 12 (4.6Cu-0.8Si)		
75	44.6	30.2	7.5
-320	50.7	42.7	4.2
-420[a]	61.5	--	2.0
	Alloy 14 (4.1Cu)		
75	37.4	31.5	2.6
-420[a]	55.3	40.0	7.0
	Alloy 16 (4.4Cu-0.3Mn-0.1V-0.1Ti)		
75	39.7	36.0	2.0
-420[a]	57.1	43.9	6.0

(a) Single machined test bar, NASA data. All samples heat treated to the T6 temper. Heat treatments are described in the 1962 Summary Report[1], pp 9 and 40.

TABLE 4. PROPERTIES OF 220 ALLOY CASTINGS IN THE HEAT-TREATED (T6) CONDITION[a]

	Alloy 11, Commercial Purity	Alloy 10, High Purity
Unnotched Tensile Properties at 75 F		
Ultimate Strength, ksi	41.8	47.8
0.2% Offset Yield Tensile Strength, ksi	25.8	25.3
Elongation, per cent	10.0	17.5
Reduction in Area, per cent	12.0	18.0
Charpy Impact Properties		
At 75 F, ft-lb	3.8, 4.0, 3.8	5.5, 6.0
At -320 F, ft-lb	1.0, 1.0, 0.8, 1.0, 3.4[b]	0.9, 0.6, 0.8, 0.7

(a) Solution heat treated 1/2 hour at 810 F, quenched in boiling, salt-saturated water solution, then aged 4 hours at 300 F. (The samples were previously solution heat treated 20 hours at 810 F and quenched.)

(b) This value appears out of line and is omitted in the average value reported in the text.

A comparison of the properties of the 220 alloy castings in the T6 temper with previously determined properties in the T4 temper is shown below:

	Commercial-Purity 220		High-Purity 220	
	T4	T6	T4	T6
Unnotched Tensile Properties at 75 F:				
Ultimate Strength, ksi	42.7	41.8	50.2	47.8
0.2% Offset Yield Tensile Strength, ksi	26.6	25.8	27.4	25.3
Elongation, per cent	10.8	10.0	19.5	17.5
Charpy Impact Properties:				
At 75 F, ft-lb	5.6	4.0	5.2	5.8
At -320 F, ft-lb	1.0	1.0	1.0	0.8

It is apparent that heat treatment to the T6 temper did not improve the 220 castings. The re-heat-treated commercial-purity casting in the T4 condition showed impact properties (at 75 F) of 6.1 ft-lb as compared with 5.6 ft-lb obtained in the original investigation. Although not examined in this program, it is possible that the less drastic quench used to solution heat treat the 220 castings contributed to their poor low-temperature properties. Additional work to examine this possibility would be desirable.

COMPARISON OF Al-Cu WITH Al-Zn-Mg CASTINGS

The work conducted during the first year of this investigation indicated that both Al-Cu and Al-Zn-Mg castings developed exceptional low-temperature properties when prepared on a super-purity aluminum base and heated treated to the T6 temper. It was decided to examine these two alloy compositions in more detail before selecting one base over the other for further alloy optimization. For maximum value in space-vehicle technology, the alloy should show good castability and weldability as well as good low-temperature properties.

A comparative rating of 195 (Al-Cu-Si) and A612 (Al-Zn-Mg-Cu) commercial-purity sand castings is given in the 1959 edition of the Alcoa Aluminum Handbook. Using an A (best) through D (worst) rating system, the two alloys compare with A356 sand castings as follows:

	Alloy		
	A356	195	A612
Strength	A	B	B
Castability	A	C	C
Resistance to corrosion	B	C	B
Weldability	B	C	C
Machinability	B	B	A
Pressure tightness	A	C	D

Although neither alloy appeared as good as A356 in this comparison, there was no clear-cut basis for selecting Al-Cu over Al-Zn-Mg casting alloys for space-vehicle usage.

To provide additional data for selection of the alloy base, two high-purity castings of the following composition were selected for study:

5.5Cu-0.15Ti
6.5Zn-1.0Mg-0.15Ti

The aluminum-copper alloy represents the maximum copper content soluble in aluminum and was designed to provide information on the best strength properties available in this system without the use of auxiliary strengtheners. Titanium was added as a grain refiner. The Al-Zn-Mg alloy represents a higher strength modification of A612. Copper was omitted from the alloy since its presence is of questionable value.[2] A titanium grain-refining addition was also added to this alloy. Sufficient metal was cast to permit measurements of mechanical properties, castability, heat-treatment response (including the necessity for solution heat treatment) and weldability.

Preparation of Castings

Al-20Cu and Al-12.5Cu-4.8Ti master alloys for use in this program were prepared from super-purity aluminum as described in the Appendix, Table A-2. In addition to the preparation of high-purity master alloys, some new alloying additions and commercial master alloys were purchased for use in preparing these alloys. These are described in the Appendix, Table A-3.

Melting procedures used in preparing the two high-purity alloys are summarized in Table 5. The detailed melting record is given in the Appendix, Table A-1. The casting included fluidity test spirals and tear-ring test castings[3] to evaluate fluidity and hot-shortness tendencies as well as keel-block and tensile-bar castings to provide material for mechanical-property evaluation. The keel-block and tensile-bar castings are shown in Figures 1 and 2. The pouring order was (1) keel block, (2) test bar, and (3) keel block. A small amount of additional metal was poured into an iron book-mold casting measuring 1-1/4 x 8 x 10 inches. This casting was poured from one end into a tilt mold unit.

The melts were made in silicon carbide crucibles and handled with graphite tools. Care was taken to avoid turbulence during alloying and casting so as to minimize oxide inclusions.

During melting, heavy drossing was noted in the Al-Zn-Mg-Ti alloy, suggesting that some magnesium might have been lost.

Evaluation of Castings

A summary of the tests performed on these two high-purity castings showing the origin of the various test samples is given in Table 6. Cutting diagrams for the keel-block castings are shown in Figure 3.

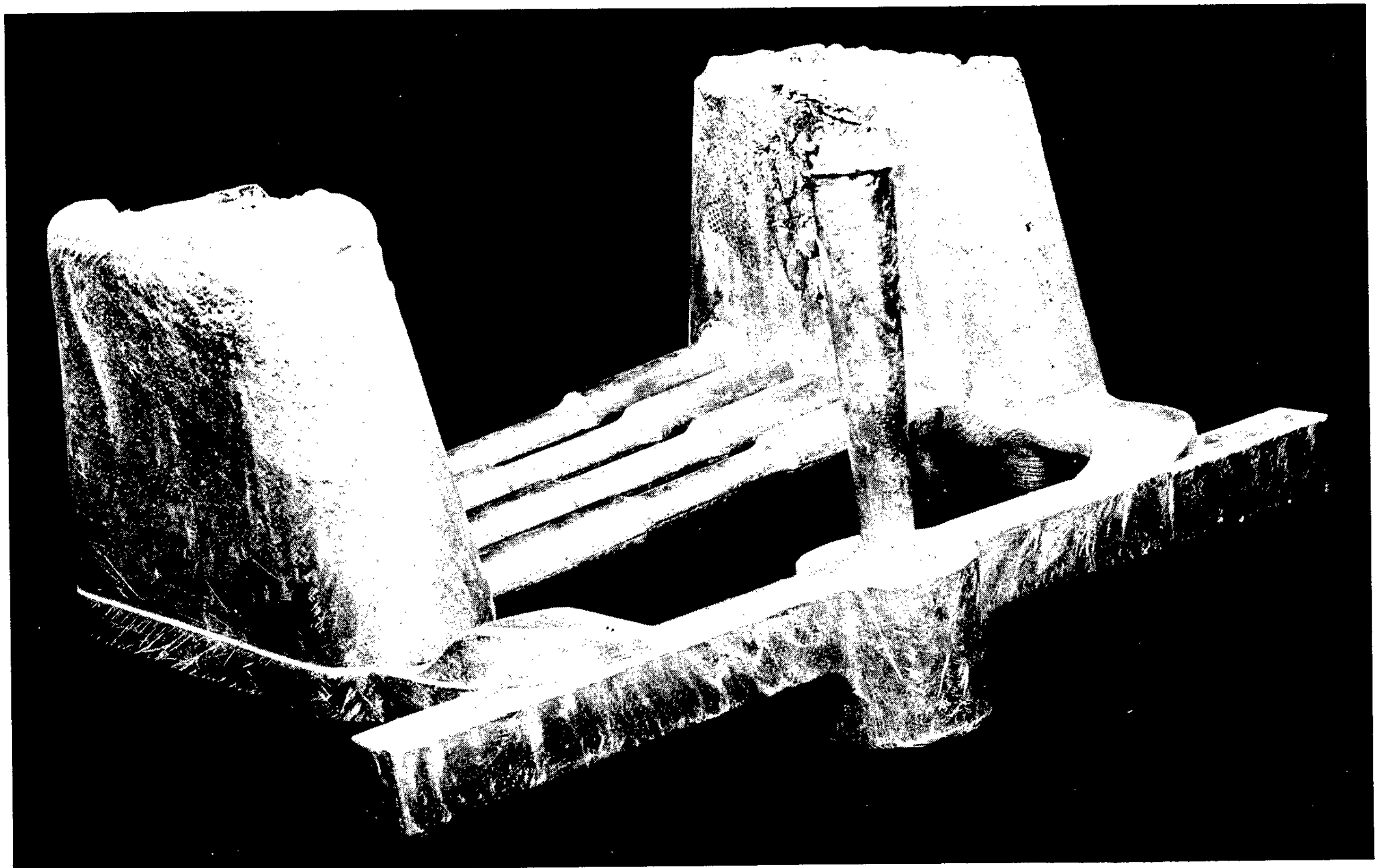

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FIGURE 1. TENSILE-BAR CASTING

Approximate weight of casting, 20 pounds.

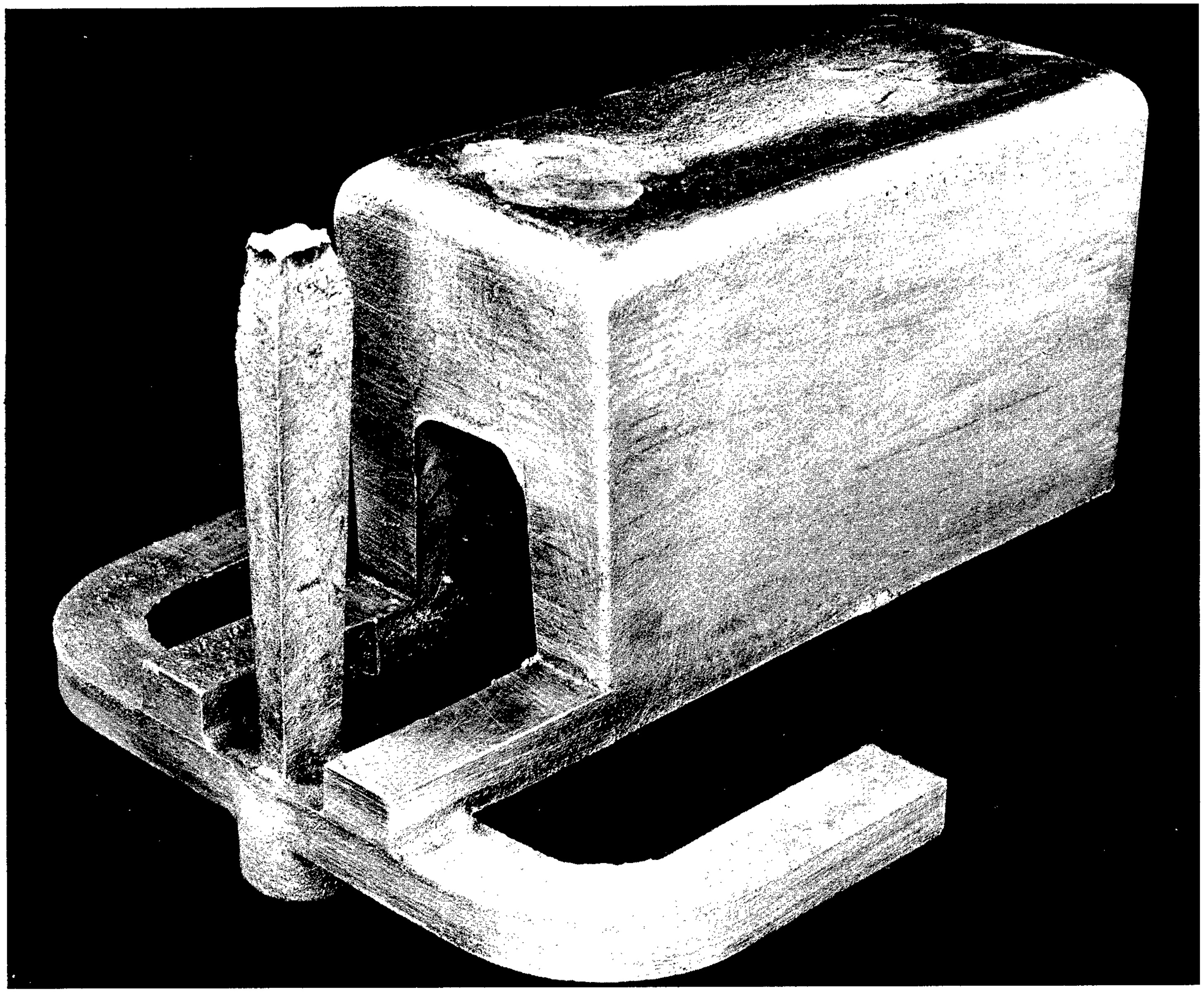

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FIGURE 2. DOUBLE-LEG KEEL-BLOCK CASTING

Approximate weight of casting, 18 pounds.

TABLE 5. OUTLINE OF MELTING PROCEDURES

Melt 17	Melt 18
(High-purity 5.5Cu-0.15Ti)	(High-purity 6.5Zn-1.0Mg-0.15Ti)
Melt aluminum	Melt aluminum
Add Al-20Cu master Add Al-6Ti master	Add magnesium Add zinc Add Al-6Ti master
Chlorinate 10 minutes Hold	Chlorinate 10 minutes Hold
Cast fluidity spirals	Cast fluidity spirals
Rechlorinate 5 minutes Hold	Rechlorinate 5 minutes Hold
Cast	Cast
2 keel blocks 1 tensile bar mold 2 tear rings 1 book mold	2 keel blocks 1 tensile bar mold 2 tear rings 1 book mold

TABLE 6. EVALUATION PROGRAM FOR Al-Cu and Al-Zn-Mg CASTINGS

Property Evaluated	Type of Test	Description of Samples		
		Type(a)	Number	Casting(b)
Castability	Hot tear test	--	1	Casting 4
	Fluidity spiral	--	1	Casting 5
	Microsection	M	1	Casting 3
Heat-treatment response	Microstructure vs. SHT Hardness vs. aging	H	1	Casting 1
Mechanical properties				
F temper (as cast)	75 F tensile test	Cast T	1	Casting 2
	75 F Charpy impact test	1	3	Casting 3
	-320 Charpy impact test	1	3	Casting 3
T5 temper (cast and aged)	75 F tensile test	Cast T	1	Casting 2
	75 Charpy impact test	1	3	Casting 3
	-320 F Charpy impact test	1	3	Casting 3
	75 F tensile test	Cast T	2	Casting 2
	75 F tensile test	T	2	Casting 1
	-320 F tensile test	T	2	Casting 1
	-420 F tensile test	T	1	Casting 3
T6 temper (SHT and aged)	75 notched tensile test, $k_t = 10$	T	2	Casting 1
	-320 F notched tensile test, $k_t = 10$	T	2	Casting 3
	75 F Charpy impact test	1	4	Casting 1
	-100 F Charpy impact test	1	4	Casting 1
	-320 F Charpy impact test	1	4 to 8	Casting 1 (and 3)
	-420 F Charpy impact test	1	4	Casting 1
	-450 F Charpy impact test	1	4	Casting 1
Weldability evaluation	75 F tensile test	W	1	Casting 3
	-320 F tensile test	W	1	Casting 3
	Side bend test	W	1	Casting 3

(a) I = impact, T = tensile, M = microsection, W = weld plates, H = heat-treatment sample.
(b) Five castings were made:

Casting 1	Double-leg keel-block casting
Casting 2	Tensile-bar (4) casting
Casting 3	Double leg keel-block casting
Casting 4	Hot tear test (3)
Casting 5	Fluidity-test spiral (several different spirals were cast)

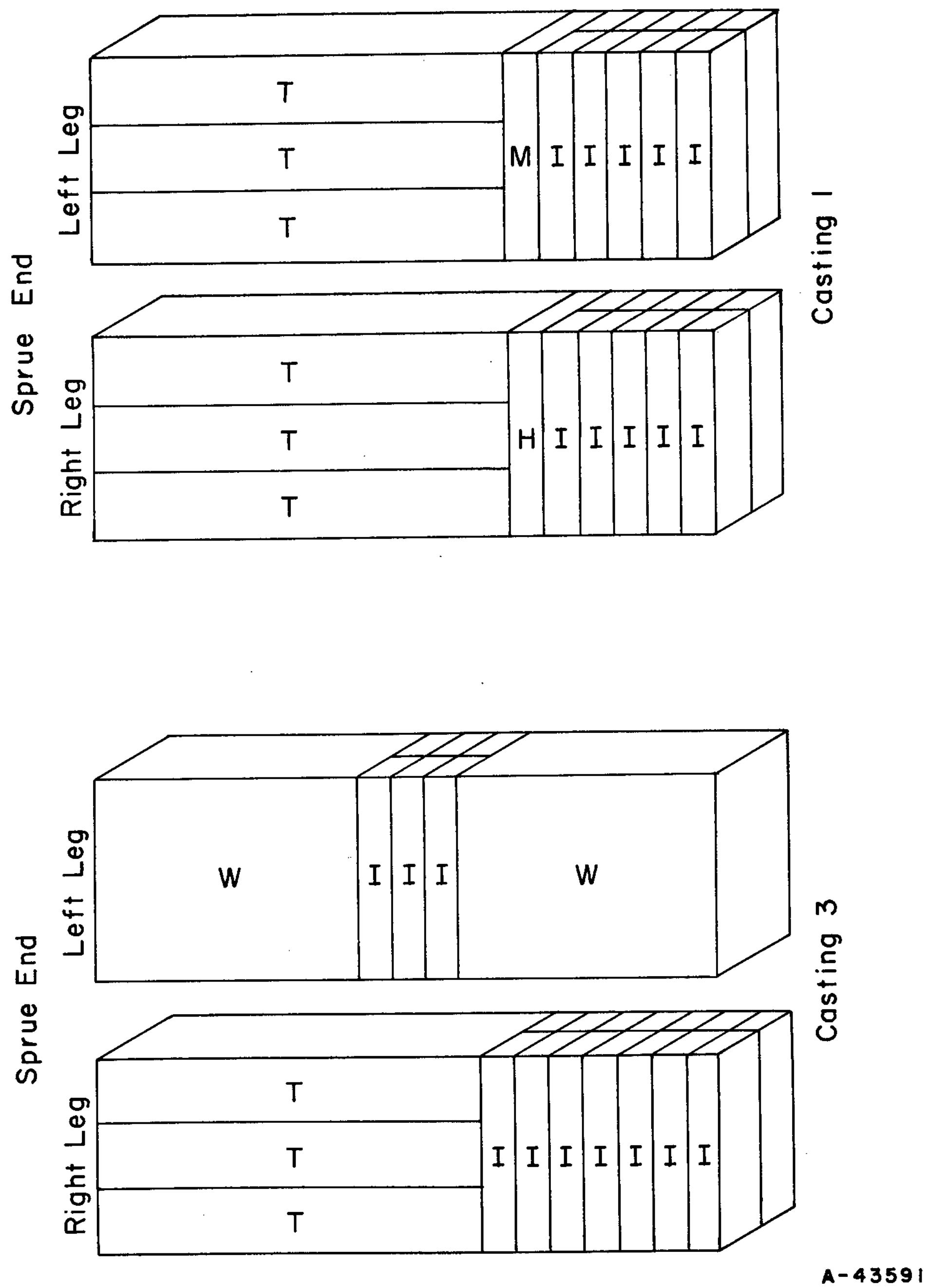

FIGURE 3. LOCATION OF SAMPLE BLANKS IN DOUBLE-LEG KEEL-BLOCK CASTINGS

T = tensile blank, I = impact blank, M = macrosection, H = heat-treatment sample, W = weld sample.

Fluidity Tests

Two types of fluidity tests were performed, a standard 3/8-inch-diameter half-round spiral cast in green sand and a "confused" spiral consisting of a thin plate section having frequent jogs and section-size offsets cast in core sand. The casting temperature was brought to 1400 F before beginning to cast the test spirals, but some drop in temperature no doubt occurred between pouring the first and the last test castings.

In the standard test spiral, Melt 17 (5.5Cu-0.15Ti) flowed a total length of 25.25 inches as compared with 34.85 inches for Melt 18 (6.5Zn-1.0Mg-0.15Ti). The confused-spiral castings (three for each alloy) are shown in Figure 4. The first two castings are plane sections of 1/16-inch thickness. The third casting includes heavy sections of 1/8 inch joined by thinner sections of 1/16 inch. Although not entirely consistent, it appears that Alloy 17 is somewhat less fluid than Alloy 18 in the confused-spiral tests.

Hot-Shortness Test

The tear-ring tests did not show much difference between the two alloys. Neither alloy showed much cracking, although one ring from Heat 18 showed complete separation in one crack. It appears that the results of these tests were not sufficiently reproducible to warrant any conclusion.

Chemical Analysis

Spectrographic analyses of material cut from the risers of the keel-block castings were made. The results of these analyses are given in Table 7. The analyses conformed very closely to the desired analyses. Titanium retention was better than observed in prior work[1], no doubt the result of the use of a titanium master alloy instead of grain-refining salts.

TABLE 7. ANALYSIS OF ALUMINUM CASTING ALLOYS

Alloy	Desired Analysis	Weight Per Cent by Analysis							
		Fe	Si	Cu	Mg	Mn	Cr	Zn	Ti
17	5.5Cu-0.15Ti	<0.01	<0.01	5.60	0.001	<0.005	<0.005	<0.01	0.08
18	6.5Zn-1.0Mg-0.15Ti	<0.01	<0.01	0.006	0.92	<0.005	<0.005	6.40	0.11

Heat-Treatment Studies

Samples cut from the keel-block castings were solution heat treated for 16 hours at temperatures between 900 and 1040 F (Al-Cu alloy) or 700 and 1040 F (Al-Zn-Mg alloy). The samples were quenched in water at 150 F. Examination of the microstructure after solution heat treatment suggested that solution heat treatment at 1020 F was optimum for both alloys. The temperature of solution heat treatment was selected as the maximum

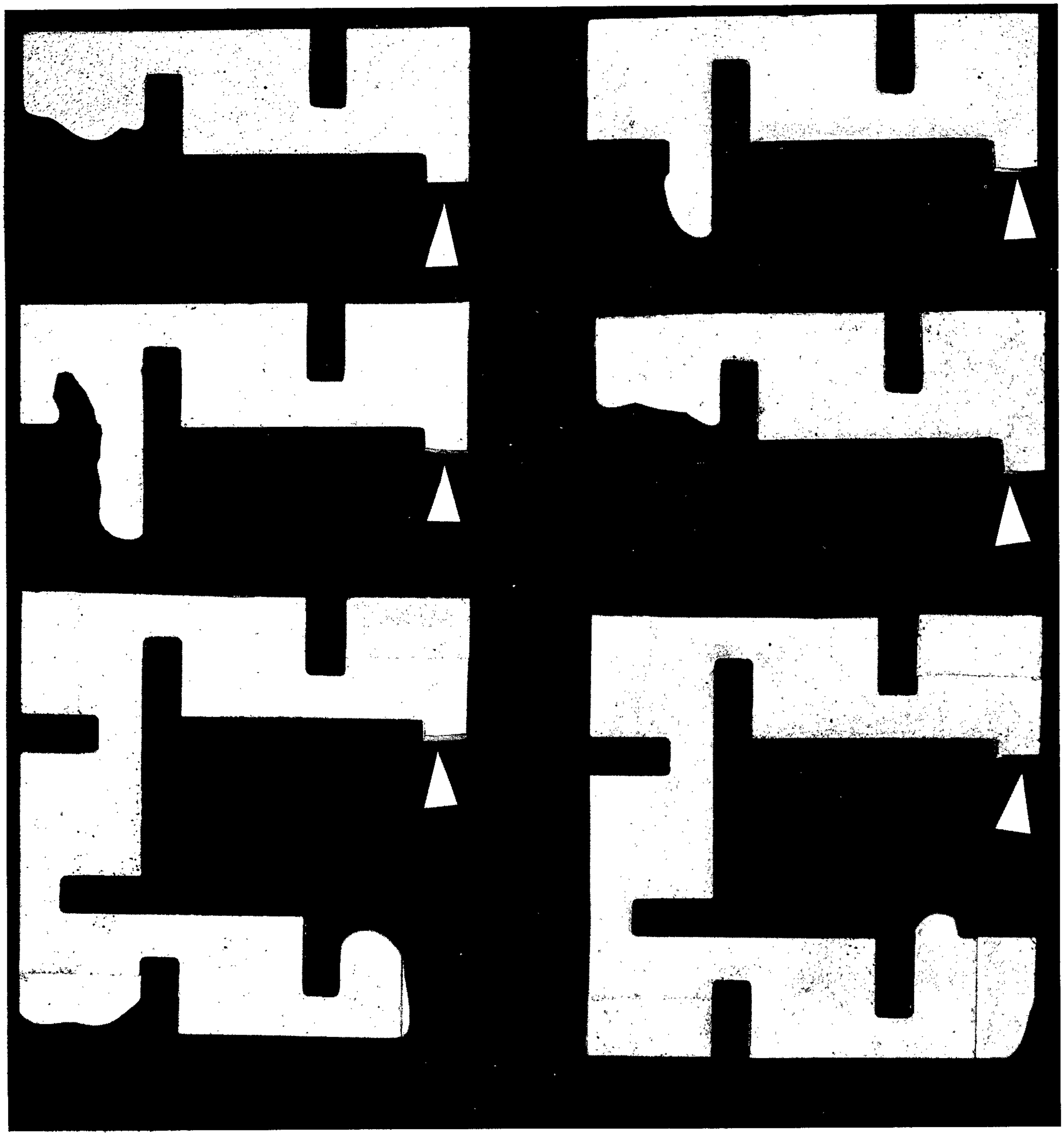

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FIGURE 4. CONFUSED SPIRAL CASTINGS

Casting temperatures, 1400 F.

temperature which did not result in grain-boundary melting or excessive grain growth. During solution heat treatment, the Vickers hardness of Alloy 17 increased from 50 (as cast) to 109. The hardness of Alloy 18 decreased from 78 to 66.

Aging treatments were examined by measuring the change in hardness as a function of aging time and temperature of samples solution heat treated from 1020 F. These data are given in Table 8. On the basis of these hardness data, it was decided to age harden Alloy 17 for 16 hours at 325 F and Alloy 18 at 8 hours at 300 F.

TABLE 8. VICKERS HARDNESS AFTER VARIOUS AGING TREATMENTS

(2.5-Kg Load)

Aging Temperature, F	Aging Time, hours									
	Alloy 17					Alloy 18				
	0 Hr	1 Hr	4 Hr	16 Hr	64 Hr	0 Hr	1 Hr	4 Hr	16 Hr	64 Hr
200						66	68	66	84	84
225						66	68	91	100	108
250						66	71	95	109	100
275						66	80	104	109	108
300	109	113	116	136	142	66	90	111	112	94
325	109	112	128	138	139	66	99	107	85	96
350	109	120	124	129	121	66	105	116	94	74
375	109	106	118	134	120					
400	109	142	133	122	106					
425	109	119	121	102	90					

Material for subsequent mechanical property evaluations was heat treated to the T6 temper as follows:

	Alloy 17	Alloy 18
Solution anneal	16 hours at 1020 F	16 hours at 1020 F
Quench	Water at 150 F	Water at 150 F
Delay period	5 days at 75 F	5 days at 75 F
Aging treatment	16 hours at 325 F	8 hours at 300 F

Material examined in the T5 temper was given the aging treatment only, while material examined in the F temper was given no heat treatment but was held 1 month at room temperature before testing.

Microstructural Examination

The macrosections cut from the keel-block castings were solution heat treated and prepared for metallographic examination for porosity, grain size, and frequency of inclusions or porosity. This latter measurement was expressed in terms of the mean free path between inclusions or porosity, the average distance which could be traversed in

any direction without intersecting an inclusion or a void. The results of the metallographic measurements are given in Table 9. During solution treatment, all of the Al-Cu phase in Alloy 17 was not dissolved. This accounts for the lower mean free path, and possibly for the small grain size, although the presence of titanium may also have affected grain size.

TABLE 9. QUANTITATIVE METALLOGRAPHIC DATA

	Alloy 17, 5.6Cu-0.1Ti	Alloy 18, 6.4Zn-0.9Mg-0.1Ti
Grain Size, mm	0.33	0.60
Mean Free Path, mm	1.0	3.0
Porosity[a], volume per cent	1.3	0.6

(a) The porosity measurement is believed to be relatively unreliable and may be in error by 1 per cent or more.

Mechanical Properties

Sample blanks were cut from the keel-block castings as shown in Figure 3 and heat treated before machining. The cast tensile samples were also heat treated as cast before machining the threaded ends.

Unnotched tensile properties were measured on standard 1/2-inch-diameter tensile specimens machined from the keel-block castings or cast to size in the test-bar casting. The test speed was 0.02 inch per minute. The stress-strain curve was recorded autographically and used to determine yield strength and elastic modulus. The tensile properties of the two high-purity castings are given in Table 10. Both alloys were unexpectedly brittle, and the yield strength of a number of test samples could not be measured. Neither alloy developed exceptional strength in the F or T5 temper. The Al-Zn-Mg alloy was much superior to the Al-Cu alloy in this respect, however. Both alloys showed a very low modulus of elasticity in the T5 temper. No explanation for this could be found in rechecking the tensile data, but these values are believed to be unreliable. The Al-Zn-Mg alloy tended to be both stronger and more ductile than the Al-Cu alloy in the T6 temper.

Notched tensile properties were measured with samples having a stress-concentration factor of 10. The samples were machined from heat-treated blanks cut from the keel-block casting. A 60-degree notch with 0.0018-inch root radius was machined circumferentially in the sample. Diameter of the sample under the notch was 0.424 inch, which resulted in a 50 per cent reduction in area at the notch. Notched tensile tests were performed at a test speed of 0.002 inch per minute. Notched tensile data are reported in Table 11. The Al-Cu alloy had poorer notched properties than the Al-Zn-Mg alloy, but appeared less sensitive to test temperature.

Charpy impact properties were measured by using standard V-notch Charpy samples tested at 18.1 ft/sec. Charpy impact data are reported in Table 12. Although the impact properties of the Al-Zn-Mg alloy were higher than those of the Al-Cu alloy,

TABLE 10. UNNOTCHED TENSILE PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS

Alloy Temper	Test Temperature, F	Type of Sample	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction In Area, per cent	Modulus of Elasticity, 10^6 psi
			Alloy 17, 5.6Cu-0.1Ti				
F	75	Cast	22.6	11.7	5.0	7.0	9.6
T5	75	Cast	22.5	8.0	3.5	4.3	3.6
T6	75	Cast	43.8	--	1.0	2.5	11.2
T6	75	Cast	40.7	--	1.0	1.5	12.7
T6	75	Machined	41.4	--	1.1	1.2	10.4
T6	75	Machined	35.0	--	0.6	<1	10.4
T6	-320	Machined	49.9	49.3	1.0	1.2	12.0
T6	-320	Machined	43.8	--	1.0	<1	10.4
			Alloy 18, 6.4Zn-0.9Mg-0.1Ti				
F	75	Cast	35.6	34.7	2.0	5.0	9.6
T5	75	Cast	40.6	--	1.1	1.2	3.5
T6	75	Cast	47.8	47.3	1.3	5.1	9.2
T6	75	Cast	46.8	46.4	0.9	2.0	9.2
T6	75	Machined	50.6	--	3.4	5.1	11.0
T6	75	Machined	52.5	51.1	2.3	3.6	11.1
T6	-320	Machined	60.0	58.4	3.0	3.2	11.6
T6	-320	Machined	61.1	59.7	1.3	2.7	9.7

TABLE 11. NOTCHED TENSILE PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS IN THE T6 TEMPER

Test Temperature, F	Ultimate Strength, ksi	Reduction In Area, per cent	Notched:Unnotched Strength Ratio[(a)]
	Alloy 17, 5.6Cu-0.1Ti		
75	40.6	2.1	1.01
75	36.6	1.7	
-320	49.5	3.2	1.15
-320	58.2	2.6	
	Alloy 18, 6.4Zn-0.9Mg-0.1Ti		
75	74.7	5.6	1.43
75	73.1	5.6	
-320	70.4	3.0	1.21
-320	76.4	2.6	--

(a) Based on comparison with unnotched tensile data from machined test samples, Table 10.

TABLE 12. IMPACT PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS

Alloy Temper	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	4	Average
		Alloy 17, 5.6Cu-0.1Ti				
F	75	2.5	2.5	2.0	--	2.3
F	-320	1.3	1.5	1.3	--	1.4
T5	75	1.5	2.0	1.5	--	1.7
T5	-320	1.6	1.2	1.1	--	1.3
T6	75	2.0	2.6	2.4	2.0	2.3
T6	-100	1.2	1.5	2.7	2.5	2.0
T6	-320	2.1	3.1	2.2	2.0	2.4
		Alloy 18, 6.4Zn-0.9Mg-0.1Ti				
F	75	3.1	3.2	3.1	--	3.1
F	-320	1.6	1.5	1.8	--	1.6
T5	75	2.0	1.9	2.0	--	2.0
T5	-320	1.9	1.2	1.8	--	1.6
T6	75	4.1	4.0	5.9	4.2	4.6
T6	-100	5.5	6.0	5.0	5.0	5.4
T6	-320	4.8	4.9	6.6	6.2	5.6

both alloys showed rather poor impact properties. Therefore, impact tests at -420 F and -450 F were not carried out.

Weld Evaluation

Because of the poor properties of Alloys 17 and 18 as determined in tests of the heat-treated material, the welding evaluation was not carried out.

Discussion of Results

The two alloys prepared in this study are compared with their closest counterparts from the previous work in Table 13. Both of the new alloys show markedly inferior impact properties and tensile ductility, and the 5.6Cu-0.1Ti alloy also shows lower tensile strength. It appears that both alloys were too highly alloyed. Therefore, it is not possible to make a valid comparison of the two bases.

On the basis of the prior work, Al-Zn-Mg alloys appear to develop superior strength:toughness properties. Also, the Al-Zn-Mg alloy appeared to have a slight

TABLE 13. A COMPARISON OF SEVERAL HIGH-PURITY CASTINGS IN THE T6 TEMPER

Alloy	Composition	Unnotched Tensile Properties[(a)], 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Notched:Unnotched Strength Ratio at -320 F	Charpy Impact Properties, ft-lb: 75 F	-320 F
17	5.6Cu-0.1Ti	38.2	--	0.8	1.15	2.3	2.4
12	4.6Cu-0.8Si	44.6	30.2	7.0	1.42	8.4	8.0
14	4.1Cu	46.2	38.0	3.1	--	10.1	14.0
18	6.4Zn-0.9Mg-0.1Ti	51.6	51.1	2.8	1.21	4.6	5.6
13	6.5Zn-0.7Mg-0.5Cu	48.6	43.5	10.2	--	10.6	14.4

(a) Machined test bars.

advantage in fluidity. However, fluidity tests are extremely temperature sensitive, and it is likely that the differences observed could be eliminated by making slight adjustments in casting temperature.

During discussions of these results with representatives of NASA, it was decided to forego a repeat of this study with less highly alloyed compositions and to concentrate additional efforts on optimization of the Al-Cu casting alloy. This decision was based principally on two considerations. First, it is likely that weldments would be made between the casting and 2219 or 2014 structural components. This would suggest that welding problems would be less if an Al-Cu casting alloy were used. Second, it was thought that shrinkage problems would be more severe in Al-Zn-Mg alloys than in Al-Cu alloys, which might limit the usefulness of the casting alloy in complex components. The decision to concentrate on Al-Cu casting alloys was based more heavily on the first consideration than on the second.

EFFECT OF MINOR COMPOSITION VARIATIONS IN 195 ALLOY

As discussed previously, the results obtained during the first year of this investigation suggested that iron, silicon, and magnesium were harmful to the low-temperature properties of high-purity alloys. However, since some undetected impurity may have affected the commercial-purity alloys, and since titanium contents varied between commercial-purity and high-purity alloys, it was thought advisable to confirm these tentative conclusions before proceeding further with extensive alloy modification of the Al-Cu alloys. For this purpose, four alloy compositions were selected for preparation on a super-purity aluminum base:

4.5Cu-0.15Ti
4.5Cu-0.8Si-0.15Ti
4.5Cu-0.8Si-0.6Fe-0.15Ti
4.5Cu-1.5Mg-0.15Ti (0.15Mg actually added)

On the basis of the previous results, the first alloy would be expected to be superior to the other three.

Preparation of Castings

High purity Al-20Cu and Al-12Si master alloys used in this program are described in the Appendix, Table A-2. The super-purity aluminum and magnesium additions are described in Table A-3 along with the commercial purity Al-6Ti and Al-50Fe master alloys.

Melting procedures used in preparing the four high-purity aluminum copper alloys are summarized in Table 14 and given in detail in the Appendix, Table A-1. The only problem noted in alloying these melts was that of adding iron to the melt of Alloy 21. The rate of solution was quite slow. Alloy 20 cooled rapidly during casting, and a poor test-bar casting resulted, which required that a portion of the heat be remelted and cast into a second test-bar mold. Fluidity-test spirals and tear-test molds were cast to check procedures. Castings made from these alloys included the keel-block and

TABLE 14. OUTLINE OF MELTING PROCEDURES

Alloy 19, 4.5Cu-0.15Ti	Alloy 20, 4.5Cu-0.8Si-0.15Ti	Alloy 21, 4.5Cu-0.8Si-0.6Fe-0.15Ti	Alloy 22, 4.5Cu-1.5Mg-0.15Ti
Melt aluminum	Melt aluminum	Melt aluminum	Melt aluminum
Add Al-Cu master Add Al-Ti master	Add Al-Cu master Add Al-Si master Add Al-Ti master	Add Al-Cu master Add Al-Si master Add Al-Fe master[(b)] Add Al-Ti master	Add Al-Cu master Add Cu-Ti master Add Al-Ti master
Chlorinate Hold	Chlorinate Hold	Chlorinate Hold[(b)]	Chlorinate Hold
Cast 2 keel blocks 1 tensile bar 1 tear ring	Cast 2 keel blocks 1 tensile bar 1 tear ring 1 book mold	Cast 2 keel blocks 1 test bar 3 fluidity spirals 1 book mold	Cast 2 keel blocks 1 tensile bar 3 fluidity spirals 1 tear ring 1 book mold
	Remelt[(a)]		
	Cast 1 tensile bar 1 book mold		

(a) The original tensile-bar casting was defective. The tensile casting, scrap from the keel blocks, and the book-mold ingot (39.1 pounds) were remelted and cast.

(b) During chlorination a large part of the Al-Fe master was found to be unmelted. An additional holding time of 45 minutes was necessary to complete solution. The melt was not chlorinated after this holding period.

tensile-bar castings shown in Figures 1 and 2, as well as a book-mold casting and several fluidity- or hot-shortness-test castings.

During subsequent testing of these alloys it was discovered that a weighing error was made in preparing the charge for Alloy 22 such that 0.15 rather than 1.5 per cent magnesium was added. Testing had progressed so far by the time this error was discovered that recasting this heat did not appear justifiable.

Evaluation of Castings

Evaluation of these four high-purity castings was limited to tests in the T6 temper. Heat treatments were selected after a preliminary hardness and microstructural survey.

Chemical Analysis

Spectrographic analyses of material cut from the risers of the keel-block castings gave the results reported in Table 15. Approximately one-third of the titanium addition was lost, but recovery of copper, silicon, and iron additions was excellent. Magnesium was added in Alloy 22 to give 0.15 per cent rather than 1.5 per cent due to a weigh-up error. Even when this error is taken into account, it is apparent that significant loss of magnesium occurred.

TABLE 15. ANALYSIS OF ALUMINUM CASTING ALLOYS

Alloy	Desired Analysis	Weight Per Cent by Analysis							
		Fe	Si	Cu	Mg	Mn	Cr	Zn	Ti
19	4.5Cu-0.15Ti	<0.01	<0.01	4.38	0.001	<0.005	<0.005	<0.01	0.09
20	4.5Cu-0.8Si-0.15Ti	<0.01	0.87	4.53	0.001	<0.005	<0.005	<0.01	0.08
21	4.5Cu-0.8Si-0.6Fe-0.15Ti	0.64	0.87	4.53	0.001	<0.005	<0.005	<0.01	0.09
22	4.5Cu-1.5Mg-0.15Ti	<0.01	<0.01	4.30	0.09(a)	<0.001	<0.005	<0.01	0.13

(a) Low magnesium content resulted from weighing error in preparing charge.

Heat-Treatment Studies

Sections cut from the keel-block casting were solution annealed for 16 hours at temperatures between 900 and 1040 F, quenched in water at 150 F, and examined for grain growth, melting, and solution of Al-Cu phase. On the basis of this study, solution-heat-treatment temperatures were selected for each alloy. These temperatures are given in Table 16, along with the hardness as cast and after solution heat treatment.

Samples of the solution-heat-treated material were aged for selected times and temperatures to determine the hardness changes during aging. These data are given in

TABLE 16. RESULTS OF SOLUTION-HEAT-TREATMENT SURVEY

Alloy	Composition	Selected Temperature[(a)], F	Vickers Hardness, 2.5-Kg Load: As Cast	Vickers Hardness, 2.5-Kg Load: Solution Heat Treated
19	4.4Cu-0.1Ti	990	45	60
20	4.5Cu-0.9Si-0.1Ti	960	54	65
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	990	52	60
22	4.3Cu-0.1Mg-0.1Ti	990	56	60

(a) Annealed 16 hours at temperature and quenched in water at 150 F.

Table 17. Although some unexplained variations are apparent in these data — all hardness data at 350 F seem low, for example — alloy trends are apparent. Silicon in Alloy 20 appears to accelerate the rate of hardening at low temperatures and also to increase the level of hardness reached after aging. The presence of iron eliminated any

TABLE 17. VICKERS HARDNESS AFTER VARIOUS AGING TREATMENTS

(2.5-Kg Load)

Alloy	Composition	Aging Time, hours	300 F	325 F	350 F	375 F	400 F	425 F
			Vickers Hardness After Aging at Indicated Temperature					
19	4.4Cu-0.1Ti	1	56	71	92	93	88	68
		4	65	98	94	103	84	70
		16	63	115	91	106	88	91
		64	81	115	111	70	84	73
20	4.5Cu-0.9Si-0.1Ti	1	83	102	93	95	100	75
		4	88	109	100	102	88	81
		16	115	127	109	107	93	78
		64	124	122	108	88	83	72
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	1	82	72	71	78	72	66
		4	88	83	82	82	71	77
		16	105	75	83	78	88	88
		64	113	83	94	86	77	70
22	4.3Cu-0.1Mg-0.1Ti	1	79	95	88	72	83	71
		4	90	105	91	71	96	94
		16	78	107	105	88	98	90
		64	100	101	111	77	93	81

effects of silicon, presumably through the formation of Al-Fe-Si intermetallic. Iron also appeared to lower the hardness reached in aging above 300 F. Magnesium in Alloy 22 appeared to retard the rate of hardening and to increase the hardness possible on aging at higher temperatures. On the basis of these data, the following aging treatments were selected:

Alloy 19	16 hours at 325 F
Alloy 20	16 hours at 325 F
Alloy 21	48 hours at 300 F
Alloy 22	16 hours at 325 F

Subsequent material for mechanical-property studies was heat treated according to the above schedule. A 5-day delay period was used between solution heat treatment and aging.

Microstructural Examination

The macrosections cut from the keel block castings were solution heat treated and prepared for metallographic examination. The sections were examined for grain size, porosity, and mean free path between porosity and intermetallics. The results of these measurements are given in Table 18. Except for Alloy 21, which contained iron, the four alloys were quite similar in appearance. The presence of iron intermetallics greatly reduced the mean free path. The iron-containing alloy also showed fairly extensive porosity. This may be more a function of casting procedure than iron content, however, since porosity was not so evident in commercial-purity 195 alloy of approximately the same composition which was prepared during the first year of this program. This alloy was held for approximately 45 minutes after chlorination because undissolved iron master was noted. It is probable that hydrogen was absorbed during this period. Although the porosity present resembled shrinkage porosity, the development of the porosity may have been aided by hydrogen rejection on freezing. Almost all of the Al-Cu phase in these alloys was dissolved during solution heat treatment, as was most of the silicon in Alloy 20. The iron intermetallic phase was unaffected by solution heat treatment, however.

TABLE 18. QUANTITATIVE METALLOGRAPHIC DATA

Alloy	Composition	Grain Size, mm	Mean Free Path, mm	Porosity(a), volume per cent
19	4.4Cu-0.1Ti	0.29	1.9	0.3
20	4.5Cu-0.9Si-0.1Ti	0.20	1.2	0.2
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	0.28	0.2	3.4
22	4.3Cu-0.1Mg-0.1Ti	0.30	1.4	0.5

(a) The values for porosity are believed to be relatively unreliable and may easily be in error by 1 per cent or more.

Mechanical Properties

Samples for mechanical property studies were cut from the keel-block castings as shown in Figure 3. The sample blanks from the keel blocks and the cast tensile bars were heat treated to a T6 temper before machining.

Unnotched tensile properties were measured as described previously. The data from these tests are given in Table 19. Notched tensile properties are reported in Table 20. The iron-containing alloy was significantly less ductile and less strong than the other alloys tested.

Charpy impact properties for these four alloys are given in Table 21. The iron-containing alloy shows the expected low-impact properties, but magnesium, contrary to expectations, was quite beneficial to impact properties. However, the magnesium-containing alloy did appear to lose some impact toughness at very low temperatures.

Weld Evaluation

Heat-treated plate sections from the keel-block castings of Alloys 19 and 22 were welded by the MIG process and evaluated in the as-welded condition. The weld-joint configuration is shown in Figure 5. Prior to welding, all surfaces of the machined joint were draw filed and degreased in acetone. One-sixteenth-inch-diameter 2319 filler wire was purchased in sealed packages to prevent moisture pickup and kept in this condition until immediately before welding. Manual tungsten arc welding was used on the first pass from the back of the weld to obtain a sound, completely fused weld. The remainder of the weld was made using the metal arc process. Welding conditions were:

Arc current setting	250
Arc voltage	20 to 25-v d-c, reverse polarity
Shielding gas	50 cfh helium
Wire feed	250 ipm
Interpass temperature	100 F or lower
Interpass cleaning	wire brush.

Seventeen passes were required with the metal arc process to complete the weld. At this point, the first tungsten-arc root pass was machined out and replaced by a metal arc weld.

Two transverse tensile bars were cut from each welded plate. One bar was tested at 75 F and the other at -320 F. The data from these tests are given in Table 22. A side-bend test sample was also cut from each welded plate. This sample as it appears after bending is shown in Figure 6. Alloy 19 failed on bending over a 3/4-inch radius, while Alloy 22 failed on bending over a 1-1/2-inch radius. Both samples failed in the weld metal.

TABLE 19. UNNOTCHED TENSILE PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS IN THE T6 TEMPER

Test Temperature, F	Type of Sample	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction In Area, per cent	Modulus of Elasticity, 10^6 psi
			Alloy 19, 4.4Cu-0.1Ti			
75	Cast	43.8	33.2	6.4	8.5	10.7
75	Cast	45.5	32.7	6.5	11.2	9.8
75	Cast	45.2	32.3	7.0	12.6	9.6
75	Cast	46.4	32.9	6.2	14.2	10.8
75	Machined	40.6	27.6	7.0	8.2	10.6
75	Machined	39.7	28.7	3.4	4.8	10.4
-320	Machined	47.8	36.4	4.7	7.4	11.9
-320	Machined	49.4	33.6	8.5	8.6	9.5
			Alloy 20, 4.5Cu-0.9Si-0.1Ti			
75	Cast	39.2	35.1	2.0	2.4	9.8
75	Cast	37.0	35.2	1.9	2.0	10.6
75	Cast	33.0	32.9	1.6	1.5	10.1
75	Cast	40.1	34.7	2.7	2.0	10.0
75	Machined	42.6	31.3	5.2	6.3	10.7
75	Machined	41.7	34.9	2.5	4.0	10.4
-320	Machined	48.5	41.6	2.9	4.3	9.8
-320	Machined	48.9	38.3	4.4	5.9	10.5
			Alloy 21, 4.5Cu-0.9Si-0.6Fe-0.1Ti			
75	Cast	34.0	29.0	2.0	2.0	10.8
75	Cast	32.7	28.2	1.9	1.5	10.5
75	Cast	34.9	28.6	2.5	2.5	9.6
75	Cast	33.2	27.8	2.0	7.9	11.2
75	Machined	25.4	25.1	1.2	<1	11.0
75	Machined	26.0	--	1.4	<1	9.6
-320	Machined	29.4	29.1	1.0	1.2	9.5
-320	Machined	28.8	--	1.0	1.2	10.0
			Alloy 22, 4.3Cu-0.1Mg-0.1Ti			
75	Cast	50.7	32.7	12.5	22.5	10.4
75	Cast	50.0	32.7	11.7	24.6	11.3
75	Cast	49.5	31.8	12.2	21.9	9.2
75	Cast	49.2	32.9	10.5	22.3	10.6
75	Machined	41.8	29.8	10.0	10.9	10.4
75	Machined	43.5	29.3	7.4	6.7	9.5
-320	Machined	50.2	31.3	5.4	7.1	10.4
-320	Machined	54.2	39.6	9.0	9.8	11.0

TABLE 20. NOTCHED TENSILE PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS IN THE T6 TEMPER (K_t = 10)

Alloy	Composition	Test Temperature, F	Notched Strength, ksi	Reduction in Area, per cent	Notched: Unnotched Strength Ratio[a]
19	4.4Cu-0.1Ti	75	53.1	7.1	1.32
		-320	62.6	2.3	1.29
20	4.5Cu-0.9Si-0.1Ti	75	51.2	5.3	1.22
		-320	63.3	2.1	1.30
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	75	32.0	2.1	1.23
		-320	33.8	1.7	1.16
22	4.3Cu-0.1Mg-0.1Ti	75	56.9	4.3	1.33
		-320	68.7	5.6	1.31

(a) Based on comparison with unnotched tensile data from machined test samples in Table 19.

TABLE 21. IMPACT PROPERTIES OF HIGH-PURITY ALUMINUM CASTINGS IN THE T6 TEMPER

Alloy	Composition, per cent	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	4	Average
19	4.4Cu-0.1Ti	75	7.7	8.0	8.2	11.2	8.8
		-100	10.7	10.8	16.0	11.9	12.3
		-320	10.9	11.1	9.0	8.9	9.9
		-420[a]	12.3	12.8	9.8	15.8	12.2
		-450[a]	10.0	13.3	16.3	11.0	12.2
20	4.5Cu-0.9Si-0.1Ti	75	6.2	6.2	6.0	6.0	6.1
		-100	7.0	6.0	8.1	6.9	7.0
		-320	5.9	7.1	6.7	5.8	6.4
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	75	2.8	3.0	2.0	2.0	2.5
		-100	2.5	3.0	2.7	3.3	2.9
		-320	2.1	2.2	2.3	2.0	2.1
22	4.3Cu-0.1Mg-0.1Ti	75	16.9	17.2	14.6	15.2	16.0
		-100	19.0	16.8	14.1	15.0	16.2
		-320	16.6	15.0	22.2	14.2	17.0
		-420[a]	9.0	9.3	10.0	9.3	9.4
		-450[a]	12.0	11.0	12.0	9.0	11.0

(a) Tests performed by NASA.

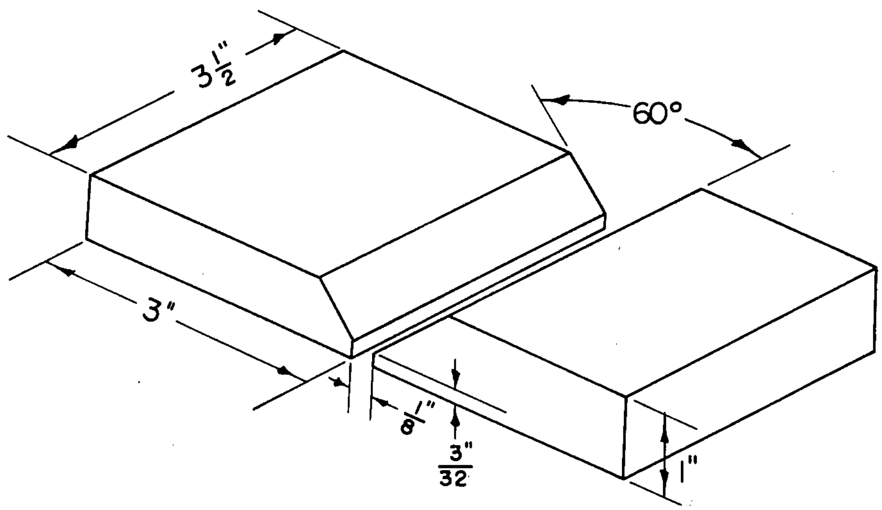

FIGURE 5. WELD-JOINT CONFIGURATION FOR WELDING PLATES FROM ALLOYS 19 AND 22

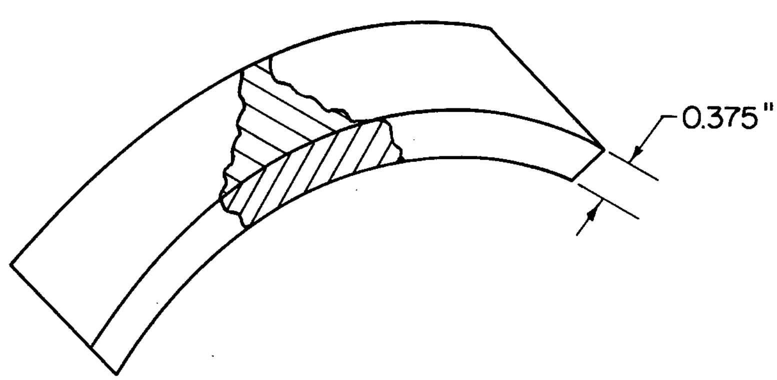

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FIGURE 6. SIDE-BEND TEST SAMPLE SHOWN AS IT APPEARS AFTER SOME DEFORMATION IN BENDING

Weld nugget indicated by shading.

TABLE 22. TENSILE PROPERTIES OF TWO HIGH-PURITY CASTING ALLOYS AS WELDED

Alloy	Composition	Test Temperature, F	Tensile Properties[(a)] Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Fracture Location[(b)]
19	4.4Cu-0.1Ti	75	32.3	14.2	10.8	10.0	HAZ
		-320	43.3	16.7	16.5	13.6	WZ/HAZ
22	4.3Cu-0.1Mg-0.1Ti	75	34.9	17.7	7.6	6.6	WZ/HAZ
		-320	39.6	20.3	4.7	5.5	WZ/HAZ

(a) Weld transverse to tension axis.
(b) HAZ = heat-affected zone;
WZ = weld zone.

Discussion of Results

The results obtained in this program are summarized in Table 23 which also includes data from prior work for comparison. Examination of these data provides additional insight into the effects of titanium, iron, silicon, and magnesium on the properties of high-purity Al-Cu castings.

It would appear that titanium is detrimental to impact strength as shown by a comparison of Alloys 19 and 14 and Alloys 20 and 12. However, this conclusion must be tempered by consideration of differences in heat treatment: Alloy 14 was solution heat treated at a somewhat higher temperature than Alloy 19, while Alloy 12 had a lower

TABLE 23. A COMPARISON OF THE PROPERTIES OF SEVERAL Al-Cu CASTINGS IN T6 TEMPER

Alloy	Composition	Unnotched Tensile Properties[(a)], 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Notched:Unnotched Strength Ratio at -320 F	Charpy Impact Properties, ft-lb: 75 F	-320 F
19	4.4Cu-0.1Ti	40.1	28.2	5.2	1.29	8.8	9.9
14	4.1Cu	46.2	38.0	3.1	--	10.1	14.0
20	4.5Cu-0.9Si-0.1Ti	42.1	33.1	3.8	1.31	6.1	6.4
12	4.5Cu-0.8Si	44.6	30.2	7.0	1.42	8.4	8.0
21	4.5Cu-0.9Si-0.6Fe-0.1Ti	25.7	25.1	1.3	1.16	2.5	2.1
6	4.6Cu-0.7Si-0.6Fe-0.1Ti[(b)]	32.8	26.0	2.2	1.05	2.0	2.0
22	4.3Cu-0.1Mg-0.1Ti	42.6	29.6	8.7	1.31	16.0	17.0

(a) Machined test bars.
(b) Commercial-purity 195 alloy.

temperature, shorter time aging treatment than did Alloy 20. Strength also appears to be lowered by titanium in the Al-Cu alloys, but this is not apparent in the Al-Cu-Si alloy.

Although it is less apparent in titanium-containing alloys than in titanium-free alloys, it is clear that silicon lowers the impact properties of Al-Cu alloys. Silicon does not appear to affect strength in a consistent manner. Ductility variations due to silicon are also inconsistent. Since silicon should not exert a major effect on castability in the small amounts added to 195 alloy (0.8 per cent) it appears that its use in a high-purity casting alloy intended for low-temperature use is unjustified.

The high-purity base 195 alloy containing an intentional iron addition, Alloy 21, is quite similar in composition to the commercial-purity 195 alloy prepared previously, Alloy 6, but its tensile properties are definitely inferior. This can no doubt be related to the rather extensive porosity developed in Alloy 21. Impact properties are comparably low, however. It appears that iron-containing intermetallic phases are a principal cause of low impact toughness in Al-Cu casting alloys.

The presence of 0.1 magnesium in a high-purity base produced an effect opposite from that expected from prior work. Although Al-Cu-Mg alloys had not been examined previously, other magnesium-containing alloys tended to show poor impact properties. Alloy 22, on the other hand, showed the highest impact toughness of any alloy tested at this point in the research program. That such a small amount of magnesium could have such a pronounced effect on impact properties is quite surprising. It seems reasonable to relate this to a Ti-Mg interaction of some type, the presence of magnesium destroying the damaging effects of titanium. This alloy also showed excellent tensile ductility. However, yield strength was low.

It was apparent on examining these data that relatively minor amounts of certain alloying additions have pronounced effects on the low-temperature impact toughness of aluminum castings. It seemed advisable, therefore, to precede further alloy optimization with an extensive screening program to gain a more exact knowledge of the effect of specific alloy additions on the properties of aluminum castings. Cost considerations precluded the extensive casting and evaluation program used to this point for screening purposes. Therefore, it was decided to perform an alloy screening study on much smaller alloy melts with a limited evaluation of properties before proceeding further with optimization of the casting-alloy composition. In agreement with the previous decision to concentrate on the Al-Cu system, alloy screening was limited to this base.

ALLOY-SCREENING STUDIES

Studies of the effects of small composition variations on the properties of high-purity Al-Cu alloys appeared desirable on the basis of the prior studies. To minimize the cost of this program, it was suggested that small heats of each alloy be prepared and cast into a 1-1/4 x 8 x 10-inch iron book mold.

Some question existed as to whether results obtained from alloys cast in iron book molds could be used to predict the properties of sand castings. To determine if this procedure was feasible, the properties of book-mold castings prepared during the casting of three former heats were compared with the properties of the sand-cast keel-block castings. Tensile tests were performed on standard 0.505-inch-diameter test samples.

Both the tensile and impact blanks were heat treated prior to final machining. These data are shown in Table 24. The tensile properties of the book-mold castings are single-test results. The impact-test values represent the average of at least three tests. Except for Alloy 14, the properties of the two castings are quite similar. Alloy 14 shows much higher tensile properties in the book-mold casting than in the sand casting. Tensile-bar castings of Alloy 14 showed the following properties:

Ultimate Tensile Strength, ksi	46.2
0.2% Offset Yield Tensile Strength, ksi	38.0
Elongation, per cent	3.1
Reduction in Area, per cent	2.4

These results parallel those found in the book-mold casting. It appears probable that this alloy is especially sensitive to cooling rate during solidification. Although it is apparent that care must be taken in predicting behavior in sand-casting from book-mold results, the agreement appeared adequate to warrant carrying out the screening program.

TABLE 24. COMPARISON OF THE PROPERTIES OF BOOK-MOLD AND SAND-MOLD CASTINGS FROM THREE HEATS

Alloy Properties in the T6 Temper	Alloy 14, 4.1Cu		Alloy 18, 6.4Zn-0.9Mg-0.1Ti		Alloy 22, 4.3Cu-0.1Mg-0.1Ti	
	Sand Casting	Book Mold	Sand Casting	Book Mold	Sand Casting	Book Mold
Unnotched Tensile Properties at 75 F[(a)]						
Ultimate Strength, ksi	37.5	46.7	51.5	49.9	42.6	45.8
0.2% Offset Yield Strength, ksi	31.5	38.9	51.1	49.5	29.6	28.7
Elongation, per cent	2.6	5.2	2.8	2.0	8.7	10.6
Reduction in Area, %	3.1	7.5	4.4	3.2	8.8	10.9
Unnotched Tensile Properties at -320 F[(a)]						
Ultimate Strength, ksi	--	54.3	60.6	56.3	52.2	60.9
0.2% Offset Yield Strength, ksi	--	41.7	59.0	55.6	35.4	41.4
Elongation, per cent	--	7.2	2.2	1.5	7.2	13.9
Reduction in Area, %	--	7.4	3.0	1.6	8.4	12.0
Charpy Impact Properties						
At 75 F, ft-lb	10.1	11.8	4.6	6.2	16.0	16.6
At -320 F, ft-lb	14.0	16.8	5.6	6.8	17.0	18.3

(a) Specimen machined from keel-block casting.

First Alloy Series

Nineteen aluminum-copper alloys were selected for screening evaluation. A brief description of the melting procedures is given in Table 25. High-purity aluminum was used for all melts, and melting was performed in clay-graphite crucibles. All melts were chlorinated. The Al-Mn, Al-Cr, and Al-Cu-Be master alloys were prepared by arc melting and are described in the Appendix, Table A-2. The Al-Cu-Ti master was prepared by conventional melting. Segregation was rather severe in this master alloy. The melt weight was approximately 10 pounds.

These melts were cast into a washed 1-1/4 x 8-1/2 x 10-inch book mold, and the slab was sectioned as shown in Figure 7 to give four tensile and eight impact blanks.

TABLE 25. MELTING PROCEDURES FOR FIRST SERIES OF SCREENING ALLOYS

Alloy	Nominal Composition	Order and Mode of Alloy Addition	Melt Temperature, F Maximum	Melt Temperature, F Casting	Special Problems
23	4.5Cu	Al:Al-20Cu	1520	1340	None
24	4.5Cu-0.1Ti	Al:Al-20Cu:Al-6Ti	1480	1370	None
25	4.5Cu-0.1Ti	Al:Al-20Cu:Al-5Cu-4Ti	1510	1370	None
26	4.5Cu-0.1Mg	Al:Al-20Cu:Mg[(a)]	1540	1330	None
27	4.5Cu-0.5Mg	Al:Al-20Cu:Mg[(a)]	1560	1330	None
28	4.5Cu-1.0Mg	Al:Al-20Cu:Mg[(a)]	1490	1410	Some burning of Mg
29	4.5Cu-1.5Mg	Al:Al-20Cu:Mg[(a)]	1520	1420	Moderate drossing
30	4.5Cu-0.1Mg-0.1Ti	Al:Al-20Cu:Al-6Ti:Mg[(a)]	1490	1420	None
31	4.5Cu-0.5Mg-0.1Ti	Al:Al-20Cu:Al-6Ti:Mg[(a)]	1565	1400	None
32	4.5Cu-0.5Mg-0.1Ti	Al:Al-20Cu:Al-5Cu-4Ti:Mg[(a)]	1525	1400	None
33	4.5Cu-1.0Zn	Al:Al-20Cu:Zn	1530	1370	None
34	4.5Cu-2.0Zn	Al:Al-20Cu:Zn	1590	1400	None
35	4.5Cu-0.3Mn	Al:Al-20Cu:Al-15Mn	1510	1420	Remelt necessary[(b)]
36	4.5Cu-0.3Mn-0.1Mg	Al:Al-20Cu:Al-15Mn:Mg[(a)]	1570	1400	None
37	4.5Cu-0.2Cr-0.1Mg	Al:Al-20Cu:Al-10Cr:Mg[(a)]	1415	1300	None
38	4.5Cu-2.0Zn-0.1Mg	Al:Al-20Cu:Zn:Mg[(a)]	1520	1380	High fluidity – mold leak
39	4.5Cu-0.1Cd	Al:Al-20Cu:Cd	1420	1400	None
40	4.5Cu-0.1Ca	Al:Al-20Cu:Ca[(a)]	1420	1300	Violent reaction with Ca
41	4.5Cu-0.1Be	Al:Al-20Cu-0.4Be	1500	1380	None

(a) Added after chlorination.
(b) Al-Mn master was not alloyed on initial melting. This was discovered after casting. The ingot was remelted and a new addition of Al-Mn master was made.

Several of these blanks were heat treated to the T6 temper as follows:

990 F for 16 hours
Quench in water at 150 F
325 F for 16 hours.

The heat-treated blanks were then machined to give Charpy impact bars or standard 1/2-inch tensile bars. Upon completion of the tests on these bars, it appeared that melting may have occurred in some of the alloys during solution heat treatment. An additional tensile bar and two additional impact bars were prepared from several of the book-mold castings and heat treated to the T6 temper as follows:

960 F for 16 hours
Quench in water at 150 F
325 F for 16 hours.

Tensile and impact tests were also performed on this material.

The tensile and impact properties of these alloys in both heat-treated conditions are given in Tables 26 and 27. Impact samples from several of the alloys were tested at -420 F by NASA. The results of these tests are also given in Table 27.

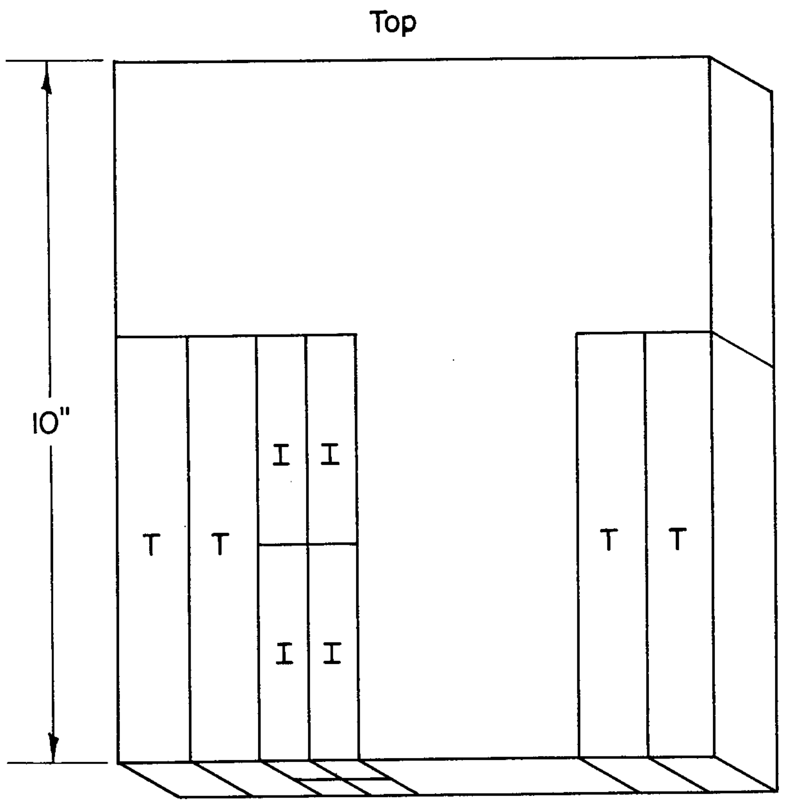


FIGURE 7. PROCEDURE FOR CUTTING BOOK MOLD CASTINGS

TABLE 26. ROOM-TEMPERATURE TENSILE PROPERTIES OF HIGH-PURITY BOOK-MOLD CASTINGS, T6 TEMPER

		Tensile Properties at 75 F				
Alloy	Nominal Composition	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Modulus of Elasticity, 10^6 psi
			Solution Heat Treated at 990 F			
23	4.5Cu	43.2	33.0	6.3	5.1	10.5
		47.7	35.3	5.5	8.2	13.8
24	4.5Cu-0.1Ti	48.6	36.9	5.3	5.8	12.2
		42.9	32.6	4.0	4.7	10.3
25	4.5Cu-0.1Ti	48.0	33.2	8.6	8.5	12.1
		44.1	34.7	4.9	7.4	10.8
26	4.5Cu-0.1Mg	45.8	37.5	3.3	6.2	10.4
		46.9	37.1	3.5	6.6	10.2
27	4.5Cu-0.5Mg	37.9	--	2.3	2.8	11.4
		39.2	38.9	2.8	6.2	9.6
28	4.5Cu-1.0Mg	15.0	--	0.5	0.8	--
		19.6	--	1.0	1.0	9.3
29	4.5Cu-1.5Mg	4.4	--	<1	0.8	--
		16.0	--	0.5	1.2	7.2
30	4.5Cu-0.1Mg-0.1Ti	53.5	36.8	9.2	10.8	12.3
		30.8	30.6	1.9	3.1	10.8
31	4.5Cu-0.5Mg-0.1Ti	58.5	44.0	10.0	11.6	11.4
		52.9	43.1	6.6	12.2	11.1
32	4.5Cu-0.5Mg-0.1Ti	53.5	42.3	8.1	10.4	11.7
		58.2	49.1	6.5	10.0	11.1
33	4.5Cu-1.0Zn	41.6	34.8	4.5	4.3	10.8
		43.4	34.1	4.1	6.2	10.2
34	4.5Cu-2.0Zn	40.7	33.9	4.5	9.7	10.5
		41.9	33.5	3.9	6.6	12.0
35	4.5Cu-0.3Mn	48.8	32.4	9.1	10.4	11.7
		54.0	35.2	12.4	14.5	11.0
36	4.5Cu-0.3Mn-0.1Mg	47.3	29.0	14.7	13.9	8.8
		42.5	25.3	12.0	14.9	10.5
37	4.5Cu-0.2Cr-0.1Mg	49.4	28.1	21.5	24.0	13.8
		46.1	27.1	14.8	13.8	9.6

TABLE 26. (Continued)

Alloy	Nominal Composition	Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Modulus of Elasticity, 10^6 psi
		Solution Heat Treated at 990 F (Continued)				
38	4.5Cu-2.0Zn-0.1Mg	43.2	32.0	6.8	8.9	11.2
		47.8	34.1	8.0	7.8	10.8
39	4.5Cu-0.1Cd	47.2	47.0	2.9	3.6	10.5
		47.9	46.2	2.0	3.5	10.5
40	4.5Cu-0.1Ca	31.4	19.6	5.8	7.7	9.0
		28.1	16.2	6.9	17.0	9.9
41	4.5Cu-0.1Be	45.8	36.8	6.0	5.8	10.2
		44.8	33.4	5.0	6.6	11.6
		Solution Heat Treated at 960 F				
23	4.5Cu	47.7	33.0	6.8	10.4	11.4
25	4.5Cu-0.1Ti	44.8	33.6	5.0	7.0	9.9
27	4.5Cu-0.5Mg	47.6	40.1	4.8	8.5	11.1
28	4.5Cu-1.0Mg	44.5	41.8	2.9	5.8	11.7
29	4.5Cu-1.5Mg	15.3	--	0.8	1.2	11.7
32	4.5Cu-0.5Mg-0.1Ti	55.9	41.9	9.1	11.9	11.4
34	4.5Cu-2.0Zn	42.8	31.8	5.0	6.2	10.2
38	4.5Cu-2.0Zn-0.1Mg	43.3	31.6	7.0	6.7	11.3

TABLE 27. IMPACT PROPERTIES OF HIGH-PURITY BOOK-MOLD CASTINGS, T6 TEMPER

Alloy	Nominal Composition	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	4	Average
			Solution Heat Treated at 990 F				
23	4.5Cu	75	9.7	10.0	8.3	--	9.3
		-320	14.9	14.3	13.4	--	14.2
24	4.5Cu-0.1Ti	75	8.7	10.1	7.8	--	8.8
		-320	13.3	13.2	9.1	--	11.8
25	4.5Cu-0.1Ti	75	12.4	11.3	10.8	--	11.5
		-320	14.1	15.0	12.5	--	13.8
26	4.5Cu-0.1Mg	75	14.8	12.9	12.3	--	13.3
		-320	13.0	18.0	14.2	--	15.0
		-420(a)	15.8	17.8	15.5	--	16.8
27	4.5Cu-0.5Mg	75	12.6	11.8	10.8	--	11.7
		-320	9.9	10.4	15.1	--	11.8
28	4.5Cu-1.0Mg	75	2.6	3.4	3.2	--	3.0
		-320	1.9	2.7	2.0	--	2.2
29	4.5Cu-1.5Mg	75	1.8	1.8	1.7	--	1.8
		-320	1.6	2.0	1.0	--	1.5
30	4.5Cu-0.1Mg-0.1Ti	75	14.8	12.4	11.3	--	12.8
		-320	16.2	16.6	14.0	--	15.6
		-420(a)	16.0	10.0	12.5	16.8	13.8
31	4.5Cu-0.5Mg.0.1Ti	75	9.2	11.2	7.6	--	9.3
		-320	10.1	10.6	10.4	--	10.3
		-420(a)	15.0	11.3	8.3	9.8	11.1
32	4.5Cu-0.5Mg-0.1Ti	75	8.5	6.3	10.9	--	8.5
		-320	7.8	9.0	13.2	--	10.0
33	4.5Cu-1.0Zn	75	10.4	10.3	9.8	--	10.1
		-320	16.7	21.1	16.9	--	18.2
34	4.5Cu-2.0Zn	75	10.3	9.8	10.1	--	10.1
		-320	21.3	16.5	14.3	--	17.3
35	4.5Cu-0.3Mn	75	16.9	15.0	12.3	--	14.7
		-320	20.4	17.1	15.0	--	17.5
36	4.5Cu-0.3Mn-0.1Mg	75	20.0	22.0	17.1	--	19.7
		-320	22.8	23.2	18.8	--	21.6
		-420(a)	14.3	20.8	16.3	22.8	19.8
37	4.5Cu-0.2Cr-0.1Mg	75	36.6	34.0	16.6	--	29.1
		-320	29.2	33.1	20.2	--	27.5
		-420(a)	21.5	22.3	17.0	22.0	20.7

TABLE 27. (Continued)

Alloy	Nominal Composition	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	4	Average
			Solution Heat Treated at 990 F (Continued)				
38	4.5Cu-2.0Zn-0.1Mg	75	16.8	16.1	15.7	--	16.2
		-320	20.8	25.0	18.4	--	21.4
		-420(a)	20.0	19.8	25.8	24.3	22.5
39	4.5Cu-0.1Cd	75	12.3	13.7	10.2	--	12.0
		-320	17.8	17.5	21.0	--	18.8
		-420(a)	20.8	17.8	22.5	25.8	21.7
40	4.5Cu-0.1Ca	75	13.1	14.0	9.3	--	12.1
		-320	14.2	16.2	8.9	--	13.1
41	4.5Cu-0.1Be	75	4.2	5.2	4.0	--	4.4
		-320	4.1	3.7	3.9	--	3.9
			Solution Heat Treated at 960 F				
23	4.5Cu	75	10.8	7.8	--	--	9.3
		-320	11.9	9.1	--	--	10.5
25	4.5Cu-0.1Ti	75	10.2	7.4	--	--	8.8
		-320	8.6	9.1	--	--	8.8
27	4.5Cu-0.5Mg	75	10.2	7.8	--	--	9.0
		-320	8.1	11.5	--	--	9.8
28	4.5Cu-1.0Mg	75	8.6	13.6	--	--	11.2
		-320	7.5	9.3	--	--	8.4
29	4.5Cu-1.5Mg	75	2.8	3.0	--	--	2.9
		-320	1.7	2.1	--	--	1.9
32	4.5Cu-0.5Mg-0.1Ti	75	8.9	8.2	--	--	8.5
		-320	8.0	7.2	--	--	7.6
34	4.5Cu-2.0Zn	75	10.1	9.8	--	--	10.0
		-320	15.0	14.2	--	--	14.6
38	4.5Cu-2.0Zn-0.1Mg	75	16.0	17.0	--	--	16.5
		-320	24.0	16.0	--	--	20.0

(a) Tests at -420 F performed by NASA.

Of the alloys in this group, the most interesting were those in which either cadmium or magnesium plus titanium were added. However, chromium, zinc, and manganese also provided interesting results in certain cases. The effects of composition are summarized in Table 28.

TABLE 28. SUMMARY OF PROPERTIES OF FIRST SERIES OF SCREENING ALLOYS IN THE T6 TEMPER

Alloy	Nominal Composition	Room-Temperature Tensile Properties: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Charpy Impact Properties, ft-lb: 75 F	-320	-420 F
		Solution Heat Treated at 990 F						
23	4.5Cu	45.4	34.2	5.9	6.6	9.3	14.2	--
24	4.5Cu-0.1Ti	45.8	35.8	4.6	5.2	8.8	11.8	--
25	4.5Cu-0.1Ti(b)	46.0	34.0	6.8	8.0	11.5	13.8	--
26	4.5Cu-0.1Mg	46.4	37.3	3.4	6.4	13.3	15.0	16.8
27(a)	4.5Cu-0.5Mg	38.6	38.3	2.6	4.5	11.7	11.8	--
28(a)	4.5Cu-1.0Mg	17.3	--	0.8	0.9	3.0	2.2	--
29(a)	4.5Cu-1.5Mg	10.2	--	0.7	1.0	1.8	1.5	--
30	4.5Cu-0.1Mg-0.1Ti	53.5	36.8	9.2	10.8	12.8	15.6	13.8
31	4.5Cu-0.5Mg-0.1Ti	55.7	43.6	8.3	11.9	9.3	10.3	11.1
32	4.5Cu-0.5Mg-0.1Ti(b)	55.8	45.7	7.3	10.2	8.5	10.0	--
33	4.5Cu-1.0Zn	42.0	34.0	4.3	5.2	10.1	18.2	--
34	4.5Cu-2.0Zn	41.3	33.7	4.2	8.2	10.1	17.3	--
35	4.5Cu-0.3Mn	51.4	32.8	10.8	12.4	14.7	17.5	--
36	4.5Cu-0.3Mn-0.1Mg	44.9	27.2	13.4	14.4	19.7	21.6	19.8
37	4.5Cu-0.2Cr-0.1Mg	47.8	27.6	18.2	18.9	29.1	27.5	20.7
38	4.5Cu-2.0Zn-0.1Mg	45.5	33.0	7.4	8.4	16.2	21.4	22.5
39	4.5Cu-0.1Cd	47.6	46.6	2.4	3.6	12.0	18.8	21.7
40	4.5Cu-0.1Ca	29.8	17.9	6.4	12.4	12.1	13.1	--
41	4.5Cu-0.1Be	45.3	35.1	5.5	5.2	4.4	3.9	--
		Solution Heat Treated at 960 F						
23	4.5Cu	47.7	33.0	6.8	10.4	9.3	10.5	--
25	4.5Cu-0.1Ti	44.8	33.6	5.0	7.0	8.8	8.8	--
27	4.5Cu-0.5Mg	47.6	40.1	4.8	8.5	9.0	9.8	--
28	4.5Cu-1.0Mg	44.5	41.8	2.9	5.8	11.2	8.4	--
29(a)	4.5Cu-1.5Mg	15.3	--	0.8	1.2	2.9	1.9	--
32	4.5Cu-0.5Mg-0.1Ti	55.9	41.9	9.1	11.9	8.5	7.6	--
34	4.5Cu-2.0Zn	42.8	31.8	5.0	6.2	10.0	14.6	--
38	4.5Cu-2.0Zn-0.1Mg	43.3	31.6	7.0	6.7	16.5	20.0	--

(a) Grain-boundary melting during solution heat treatment.
(b) Alloy made with Al-Cu-Ti master.

A series of age-hardening studies were performed on samples of several of these screening alloys. These data are given in Table 29. It is apparent that the aging-treatment schedule -- 16 hours at 325 F -- produces appreciable hardening. In general, the hardness data correlate quite well with yield-strength data. The principal deviation from this correlation was observed in Alloy 39, which was softer than might have been expected. Metallographic examination showed considerable grain-boundary precipitation in this alloy after aging. Other points of interest in these data are listed below:

TABLE 29. HEAT-TREATMENT RESPONSE OF SELECTED HIGH-PURITY BOOK-MOLD CASTINGS

Alloy	Nominal Composition	Solution Heat Treatment Temperature, F	Aging Temperature, F	Rockwell B Hardness After Indicated Aging Time[a]				
				As Solution Heat Treated	1 Hr	4 Hr	16 Hr	64 Hr
23	4.5Cu	960	325	43	47	54	67	49
		990	325	46	44	51	65	53
24	4.5Cu-0.1Ti	990	325	31	37	49	63	48
26	4.5Cu-0.1Mg	960	325	47	53	59	70	50
		990	325	52	52	55	68	48
27	4.5Cu-0.5Mg	960	325	61	52	61	75	53
31	4.5Cu-0.5Mg-0.1Ti	960	325	56	55	62	73	54
35	4.5Cu-0.3Mn	990	325	33	37	56	65	49
		990	300	36	40	48	59	47
36	4.5Cu-0.3Mn-0.1Mg	990	325	53	32	36	49	44
		990	300	39	34	37	45	42
37	4.5Cu-0.2Cr-0.1Mg	990	325	42	33	40	60	48
		990	300	42	44	49	51	47
38	4.5Cu-2.0Zn-0.1Mg	990	325	44	33	43	60	41
39	4.5Cu-0.1Cd	990	350	21	20	33	53	39
		990	325	21	17	23	62	48

(a) Each reported value is the average of at least three impressions.

(1) Titanium, manganese, cadmium, and probably chromium suppress room-temperature aging while magnesium accelerates it, based on hardness as solution heat treated. Cadmium is most effective.

(2) Cadmium also retards aging during the initial phases of aging at 325 and 350 F.

(3) In the two alloys examined, aging response was not affected greatly by dropping the solution-heat-treatment temperature from 990 to 960 F. In both cases, however, hardness was higher after quenching from 960 F.

(4) In the four alloys examined, hardness was higher after aging at 325 F than after aging at 300 F (three alloys) or 350 F (one alloy).

To examine the grain-boundary reaction in the Al-Cu-Cd alloy in more detail, samples of Alloy 39 were quenched from 4 different solution temperatures after 16 hours at temperature and then aged for 16 hours at 325 F, 16 hours at 350 F, or 8 hours at 375 F. The Rockwell B hardness of these samples varied as follows:

Solution Treatment Temperature, F	Rockwell B Hardness As Quenched	325 F	350 F	375 F
990	23	73	69	61
975	24	68	61	61
960	21	68	61	61
945	24	71	65	60

The grain-boundary phase was present after all aging treatments. A slight decrease in amount of this phase may have resulted from low-temperature aging treatments and high-temperature solution heat treatments, but the differences were small. The grain-boundary phase was not present in solution-heat-treated samples. The hardness of this alloy as cast was Rockwell B 10. The hardness after aging 16 hours at 325 F was higher than that represented in Table 29. Hardness impressions on tensile and impact samples suggested that the value given in Table 29 is in error.

Second Alloy Series

The striking improvements in yield strength resulting from the presence of cadmium in aluminum-copper alloys plus the questions raised regarding the benefits of additions of zinc, chromium, manganese, magnesium, and titanium suggested the need for additional alloy-screening studies. Twelve new compositions were therefore selected for study. The melting procedures for these alloys, also cast into 10-pound iron-book-mold castings, are described in Table 30. All melts were made in clay-graphite crucibles and were chlorinated 10 minutes prior to casting.

The evaluation of these castings paralleled that used for the first series of screening alloys. The bulk of the material was heat treated after cutting sample blanks as follows:

980 F for 16 hours
Quench in water at 50 F
325 F for 16 hours.

The slightly lower solution-heat treatment temperature was used to minimize the possibility of melting, and a cold-water quench was used to reduce the possibility of grain-boundary precipitation in cadmium alloys. Two of the alloys, Alloys 45 and 49, were also precipitation hardened at 370 F for 6 hours. It was thought that a higher precipitation-hardening temperature might improve tensile ductility.

The results of tensile and impact tests on these alloys are given in Tables 31 and 32. These data are summarized in Table 33. In the two alloys tested, no obvious benefit from the use of a higher aging temperature is apparent, although Alloy 49 did show slightly higher tensile ductility. The cadmium-containing alloys appear relatively insensitive to aging temperature. Alloy 52 is obviously deficient in copper, and must be disregarded in examining these data for alloying trends. Also, the mechanical properties obtained for Alloys 48 and 50 suggest that some melting may have occurred during solution heat treatment.

TABLE 30. MELTING PROCEDURES FOR SECOND SERIES OF SCREENING ALLOYS

Alloy	Nominal Composition	Order and Mode of Alloy Addition	Melt Temp, F	
			Maximum	Casting
42	4.5Cu-0.2Cr	Al:Al-20Cu:Al-10Cr	1410	1300
43	4.5Cu-0.1Cd-0.2Cr	Al:Al-20Cu:Al-10Cr:Cd	1420	1320
44	4.5Cu-0.1Cd-0.2Cr-0.1Ti	Al:Al-20Cu:Al-6Ti:Al-10Cr:Cd	1470	1320
45	4.5Cu-0.1Cd-0.1Ti	Al:Al-20Cu:Al-6Ti:Cd	1500	1400
46	4.5Cu-0.1Cd-0.1Mg	Al:Al-20Cu:Cd:Mg[a]	1510	1365
47	4.5Cu-0.1Cd-0.1Mg-0.1Ti	Al:Al-20Cu:Al-6Ti:Cd:Mg[a]	1455	1380
48	4.5Cu-0.1Cd-0.2Mn	Al:Al-20Cu:Al-15Mn:Cd	1480	1400
49	4.5Cu-0.1Cd-2.0Zn	Al:Al-20Cu:Zn:Cd	1475	1350
50	4.5Cu-2.0Zn-0.25Mg-0.1Cd	Al:Al-20Cu:Zn:Cd:Mg[a]	1480	1350
51	4.5Cu-2.0Zn-0.25Mg	Al:Al-20Cu:Zn:Mg[a]	1490	1410
52	4.5Cu-2.0Zn-0.1Mg-0.1Ti	Al:Al-20Cu:Al-6Ti:Zn:Mg[a]	1490	1400[b]
53	4.5Cu-0.1Cd-2.0Zn-0.1Cr-0.1Mg	Al:Al-20Cu:Zn:Cd:Al-10Cr:Mg[a]	1470	1420

(a) Magnesium added after chlorination.
(b) After casting a small puddle of aluminum was observed in the bottom of the furnace. This is believed to have come from a portion of Al-20Cu master which fell out of the crucible during meltdown.

TABLE 31. ROOM-TEMPERATURE TENSILE PROPERTIES OF HIGH-PURITY BOOK-MOLD CASTINGS, T6 TEMPER

		Tensile Properties at 75 F				
Alloy	Nominal Composition	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Modulus of Elasticity, 10^6 psi
		Age Hardened for 16 Hours at 325 F				
42	4.5Cu-0.2Cr	46.0	25.9	17.5	18.1	10.7
		44.5	26.9	13.1	13.2	11.1
43	4.5Cu-0.1Cd-0.2Cr	51.2	42.1	4.0	6.0	11.0
		45.6	38.2	2.8	2.3	10.1
44	4.5Cu-0.1Cd-0.2Cr-0.1Ti	58.6	54.9	6.1	6.2	14.0
		55.6	52.0	3.5	5.4	9.7
45	4.5Cu-0.1Cd-0.1Ti	57.8[a]	53.9[a]	3.4[a]	3.9[a]	11.5[a]
		49.2[b]	-- [b]	2.0[b]	3.6[b]	10.3[b]
46	4.5Cu-0.1Cd-0.1Mg	47.3	39.2	7.3	6.1	11.5
		43.9	39.4	5.6	7.4	9.8
47	4.5Cu-0.1Cd-0.1Mg-0.1Ti	56.2	47.2	11.1	17.1	10.7
		54.1	44.9	9.5	9.6	10.7
48	4.5Cu-0.1Cd-0.2Mn	57.4	--	1.4	3.2	10.2
		60.8	59.9	1.9	3.9	10.0
49	4.5Cu-2.0Zn-0.1Cd	45.4[a]	45.1[a]	1.5[a]	3.9[a]	10.0[a]
		43.2	41.3	2.2	3.2	9.7
50	4.5Cu-2.0Zn-0.1Cd-0.25Mg	55.6	--	2.0	2.2	10.3
		64.9	--	1.6	4.7	10.5
51	4.5Cu-2.0Zn-0.25Mg	42.3	33.0	9.5	16.3	11.0
		43.9	34.4	11.5	17.0	9.7
52[c]	4.5Cu-2.0Zn-0.1Mg-0.1Ti	42.8	24.6	19.9	38.4	11.0
		43.7	24.8	24.1	35.4	10.4
53	4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	50.5	48.5	8.8	10.3	10.0
		51.4	43.4	8.1	11.5	10.4
		Age Hardened for 6 Hours at 370 F				
45	4.5Cu-0.1Cd-0.1Ti	59.9	53.4	3.5	5.1	10.7
49	4.5Cu-2.0Zn-0.1Cd	45.0	39.4	4.7	3.9	9.0

(a) These samples accidentally placed in aging furnace at 370 F. They were subsequently removed, re-solution heat treated 1/2 hr at 980 F, and aged at 325 F.

(b) This is believed to represent a bad test bar and the results are not considered reliable.

(c) This alloy may be low in copper.

TABLE 32. IMPACT PROPERTIES OF HIGH-PURITY BOOK-MOLD CASTINGS, T6 TEMPER

Alloy	Nominal Composition	Test Temp, F	Charpy Impact Properties[a], ft-lb 1	2	3	4	Average
			Age Hardened for 16 Hours at 325 F				
42	4.5Cu-0.2Cr	75	17.8	17.4	20.4	14.8	17.6
		-320	20.0	19.2	23.7	15.2	19.5
43	4.5Cu-0.1Cd-0.2Cr	75	10.4	13.2	13.8	12.2	12.4
		-320	18.5	14.0	15.8	13.2	15.3
44	4.5Cu-0.1Cd-0.2Cr-0.1Ti	75	6.3	5.5	5.0	5.3	5.5
		-320	14.1	11.2	11.1	9.6	11.5
45	4.5Cu-0.1Cd-0.1Ti	75	3.1[b]	4.9[b]	7.0	13.5	7.2
		-320	7.5[b]	7.8[b]	--	--	7.6
		-420	9.7	7.3	6.3	10.3	8.4
46	4.5Cu-0.1Cd-0.1Mg	75	20.2	21.0	14.6	23.1	19.7
		-320	25.3	23.1	30.2	25.3	25.9
		-420	27.0	34.6	30.4	26.0	29.5
47	4.5Cu-0.1Cd-0.1Mg-0.1Ti	75	11.7	11.8	12.8	17.4	13.4
		-320	23.0	22.6	13.0	13.1	17.9
		-420	25.5	18.0	13.5	11.3	17.1
48	4.5Cu-0.1Cd-0.2Mn	75	3.7	4.0	2.1	2.8	3.1
		-320	3.0	3.7	2.4	3.1	3.0
49	4.5Cu-0.1Cd-2.0Zn	75	9.5[b]	8.8[b]	12.0	11.9	10.0
		-320	20.2[b]	19.1[b]	17.3	18.0	18.6
		-420	14.9	19.3	28.3	17.5	20.0
50	4.5Cu-0.1Cd-2.0Zn-0.25Mg	75	2.6	3.1	3.0	3.1	2.9
		-320	3.1	2.5	3.1	2.2	2.7
51	4.5Cu-2.0Zn-0.25Mg	75	17.2	18.0	20.2	14.0	17.3
		-320	24.2	25.2	18.9	26.3	23.6
		-420	31.8	26.5	20.8	16.8	24.0
52[c]	4.5Cu-2.0Zn-0.1Mg-0.1Ti	75	26.8	16.2	14.8	18.1	18.9
		-320	21.3	19.6	20.1	21.2	20.5
53	4.5Cu-0.1Cd-2.0Zn-0.1Cr-0.1Mg	75	20.2	17.3	19.8	17.4	18.7
		-320	26.4	22.4	16.0	17.0	20.4
		-420	26.8	30.8	21.3	--	20.3
			Age Hardened for 6 Hours at 370 F				
45	4.5Cu-0.1Cd-0.1Ti	75	5.2	5.0	4.3	--	4.8
		-320	7.6	6.1	5.8	--	6.5
49	4.5Cu-0.1Cd-2.0Zn	75	9.0	11.0	--	--	10.0

(a) Tests at -420 F performed by NASA.

(b) These samples accidentally placed in aging furnace at 370 F. They were subsequently removed, re-solution heat treated 1/2 hour at 980 F, and aged at 325 F.

(c) This alloy may be low in copper.

TABLE 33. SUMMARY OF PROPERTIES OF SECOND SERIES OF SCREENING ALLOYS IN THE T6 TEMPER

Alloy	Nominal Composition	Room-Temperature Tensile Properties: Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Impact Properties, ft-lb: 75 F	-320 F	-420F
		Age Hardened for 16 Hours at 325 F						
42	4.5Cu-0.2Cr	45.2	26.4	15.3	15.8	17.6	19.5	--
43	4.5Cu-0.1Cd-0.2Cr	48.4	40.2	3.4	4.2	12.4	15.3	--
44	4.5Cu-0.1Cd-0.2Cr-0.1Ti	57.1	53.4	4.8	5.8	5.5	11.5	--
45	4.5Cu-0.1Cd-0.1Ti	57.8	53.9	3.4	3.8	7.2	7.6	8.4
46	4.5Cu-0.1Cd-0.1Mg	46.6	39.3	6.4	6.8	19.7	25.9	29.5
47	4.5Cu-0.1Cd-0.1Mg-0.1Ti	55.2	46.0	10.3	13.4	13.4	17.9	17.1
48(a)	4.5Cu-0.1Cd-0.2Mn	59.1	--	1.5	3.6	3.1	3.0	--
49	4.5Cu-2.0Zn-0.1Cd	44.3	43.2	1.8	3.6	10.6	18.6	20.0
50(a)	4.5Cu-2.0Zn-0.1Cd-0.25Mg	60.2	--	1.8	3.4	2.9	2.7	--
51	4.5Cu-2.0Zn-0.25Mg	43.1	33.9	10.5	16.6	17.3	23.6	24.0
52(b)	4.5Cu-2.0Zn-0.1Mg-0.1Ti	43.2	24.7	22.0	37.9	18.9	20.5	--
53	4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	51.0	46.0	8.4	10.9	18.7	20.4	20.3
		Age Hardened for 6 Hours at 370 F						
45	4.5Cu-0.1Cd-0.1Ti	59.3	53.4	3.5	5.1	4.8	6.5	--
49	4.5Cu-2.0Zn-0.1Cd	45.0	39.4	4.7	3.9	10.0	--	--

(a) Grain-boundary melting during solution heat treatment suspected.
(b) This alloy suspected to be low in copper.

Alloying Trends

Portions of the data obtained in the two screening-alloy studies are grouped in Table 34 in a manner intended to illustrate alloying trends. In this table, the change in tensile or impact properties resulting from additions of cadmium, magnesium, chromium, titanium, zinc, and manganese are presented. The following alloying trends may be seen:

Cadmium

Cadmium results in marked increase in yield strength. However, it generally reduces tensile ductility and as a result is less effective in increasing ultimate strength.

TABLE 34. ALLOYING EFFECTS IN HIGH-PURITY BOOK-MOLD CASTINGS
(All alloys in T6 temper)

		Change in Properties Resulting From Selected Alloy Additions[a]			
Alloys Being Compared	Alloy Numbers	Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	-320 F Impact, ft-lb
		Effects of 0.1 Cd Addition			
4.5Cu	23 vs. 39	+2.2	+12.4	-3.5	+4.6
4.5Cu-0.1Mg	26 vs. 46	+0.2	+2.0	+3.0	+10.9
4.5Cu-2.0Zn	34 vs. 49	+3.0	+9.5	-2.4	+1.3
4.5Cu-0.2Cr	42 vs. 43	+3.2	+13.8	-11.9	-4.2
4.5Cu-0.1Ti	24 & 25 vs. 45	+11.9	+19.5	-2.3	-5.2
4.5Cu-0.1Mg-0.1Ti	30 vs. 47	+1.7	+9.2	+1.1	+2.1
		Effects of 0.1 Mg Addition			
4.5Cu	23 vs. 26	+1.0	+3.1	-2.5	+0.8
4.5Cu-2.0Zn	34 vs. 38	+4.0	-0.7	+3.2	+4.1
4.5Cu-0.2Cr	42 vs. 37	+2.6	+1.2	+2.8	+6.0
4.5Cu-0.1Ti	24 & 25 vs. 30	+7.6	+2.4	+3.5	+3.0
4.5Cu-0.3Mn	35 vs. 36	-6.5	-6.6	+2.6	+4.1
4.5Cu-0.1Cd	39 vs. 46	-1.0	-7.3	+4.0	+7.1
4.5Cu-0.1Cd-0.1Ti	45 vs. 47	-2.6	-7.9	+6.9	+10.9
		Effects of 0.1 Ti Addition			
4.5Cu	23 vs. 24 & 25	+0.5	+0.2	-0.2	-1.4
4.5Cu-0.1Mg	26 vs. 30	+7.1	-0.5	+5.8	+0.8
4.5Cu-0.1Cd	39 vs. 45	+10.2	+7.3	+1.0	-11.2
4.5Cu-0.1Cd-0.1Mg	46 vs. 47	+8.6	+6.7	+3.9	-8.0
4.5Cu-0.1Cd-0.2Cr	43 vs. 44	+8.7	+13.2	+1.4	-3.8
		Effects of 0.2Cr Addition			
4.5Cu	23 vs. 42	-0.2	-7.8	+9.4	+5.3
4.5Cu-0.1Mg	26 vs. 37	+1.4	-9.7	+14.8	+12.5
4.5Cu-0.1Cd	39 vs. 43	+0.8	-6.4	+1.0	-3.5
4.5Cu-0.1Cd-0.1Ti	45 vs. 44	-0.7	-0.5	+1.4	+4.5
		Effects of 0.3 Mn Addition			
4.5Cu	23 vs. 35	+6.4	-0.4	+4.9	+3.3
4.5Cu-0.1Mg	26 vs. 36	-1.5	-10.1	+10.0	+6.6
		Effects of 2.0 Zn Addition			
4.5Cu	23 vs. 34	-4.1	-0.5	-1.7	+3.1
4.5Cu-0.1Mg	26 vs. 38	-1.1	-4.3	+4.0	+6.4
4.5Cu-0.1Cd	39 vs. 49	-3.3	-3.4	-0.6	-0.2

(a) A positive change indicates that the addition considered increased the alloy property by the amount listed in the table. For example, the changes in properties resulting from addition of 0.1Cd to Al-4.5Cu (23 vs. 39) were:

	23	39	Change
Ultimate Tensile Strength	45.4	47.6	+2.2
Yield Strength	34.2	46.6	+12.4
Elongation	5.9	2.4	-3.5
Impact Properties	14.2	18.8	+4.6

Impact properties also tend to be improved by cadmium, although the effect is not consistent. Exceptions to these trends are apparent in certain alloys and may indicate an overriding effect of one of the other alloying additions.

Magnesium

Magnesium increased impact properties in every case and increased tensile elongation in every case but one. Its effects on ultimate and yield strength were less consistent. In both cadmium-containing alloys, a rather large decrease in yield strength was observed, but this seems more than compensated for by increases in tensile ductility and impact properties. In cadmium-free alloys (except the manganese alloy) it appears to improve strength moderately.

Titanium

Titanium generally produced significant increases in ultimate strength, yield strength, and elongation. When cadmium was present, it resulted in quite large reductions in impact properties. Since the beneficial effects of titanium on tensile properties are believed related to its grain-refining effects, one might assume that fine grain size in cadmium alloys is detrimental to impact strength.

Chromium

Chromium appears to improve impact properties and tensile ductility, although it is less effective in cadmium-containing alloys. In most cases, it reduced yield strength and had little effect on tensile strength.

Manganese

Very little data are available on manganese additions. In the two comparisons given in Table 34, manganese appears to behave similarly to chromium.

Zinc

Zinc improved tensile ductility and impact properties in the magnesium-containing alloy. In the other alloys examined it appears to be of little usefulness and perhaps may even be undesirable.

Interactions

Some caution is necessary in analyzing alloying effects by studying changes in the manner outlined in Table 34. A strong effect in one direction from a specific element may be largely overshadowed by the presence of another element in the alloy. For example, in comparing Alloys 26 (4.5Cu-0.1Mg), 39 (4.5Cu-0.1Cd) and 46 (4.5Cu-0.1Cd-0.1Mg), it appears that in the presence of magnesium, cadmium is much less effective than usual in increasing strength, and instead results in rather striking improvements

in tensile ductility and impact properties. Some type of Mg-Cd interaction is suggested by these results. Other similar interactions can be suggested by a close review of the data in Table 34.

Discussion of Results

It is also important to note that large improvements in properties in Table 34 often denote a rather poor base, and a small effect often results when the base alloy has excellent properties. It is perhaps more reliable to select the most useful combination of alloying additions by reference to a plot of the data such as that shown in Figure 8. In this case, impact strength at -320 F is plotted versus yield strength at 75 F for a number of the more interesting screening alloys. Tensile ductility is indicated beside each point of this plot, while those alloys containing cadmium are indicated by an arrow under the point. The position of HP 195 is included on this graph as a point of reference. The advantages of cadmium in the alloy are quite striking. Also, a check of elongation values of the cadmium-containing alloys shows that Alloys 46, 47, and 53, which contain magnesium, are superior to Alloys 39, 43, 44, and 49, which do not contain magnesium. A comparison of the positions of Alloy 47 with Alloy 46 suggests that a trade-off of increased tensile ductility and yield strength at the expense of impact resistance occurs with addition of titanium. A similar trade-off is indicated with addition of zinc and chromium in comparing Alloys 46 and 53. Other compositions of interest are 4.5Cu-2Zn-0.1 to 0.25Mg, Points 38 and 51, where additional magnesium is definitely beneficial, and 4.5Cu-0.1Ti-0.1 to 0.5Mg, Points 30 and 31, where increased magnesium increased strength at the expense of impact resistance without affecting tensile ductility.

On the basis of the analyses of the properties of the book-mold castings, and noting that a minimum yield strength of 35 ksi was desired, three alloy compositions appeared worthy of full-scale evaluation:

(1) 4.5Cu-2.0Zn-0.1Mg-0.1Cr-0.1Cd (Alloy 53)
(2) 4.5Cu-0.1Cd-0.1Mg-0.05Ti (a compromise between Alloys 46 and 47)
(3) 4.5Cu-0.25Mg-0.1Ti (a compromise between Alloys 30 and 31).

The presence of zinc in the first alloy probably serves no useful purpose, but the possibility of an unsuspected interaction exists, so its inclusion was considered desirable.

ALLOY SCALE-UP STUDIES

The three high-purity aluminum casting alloys worthy of full-scale evaluation were prepared as 65-pound melts, cast into sand molds, and evaluated. In addition to the casting of the keel-block castings of the type shown in Figure 2, it was decided to cast four pump housings from each alloy. The configuration of this casting is shown in Figure 9. The pattern for this casting was supplied by NASA. To provide sufficient material for preparing these castings, at least two melts of each alloy were required. Problems in casting the pump-house configuration necessitated more than two melts in every case.

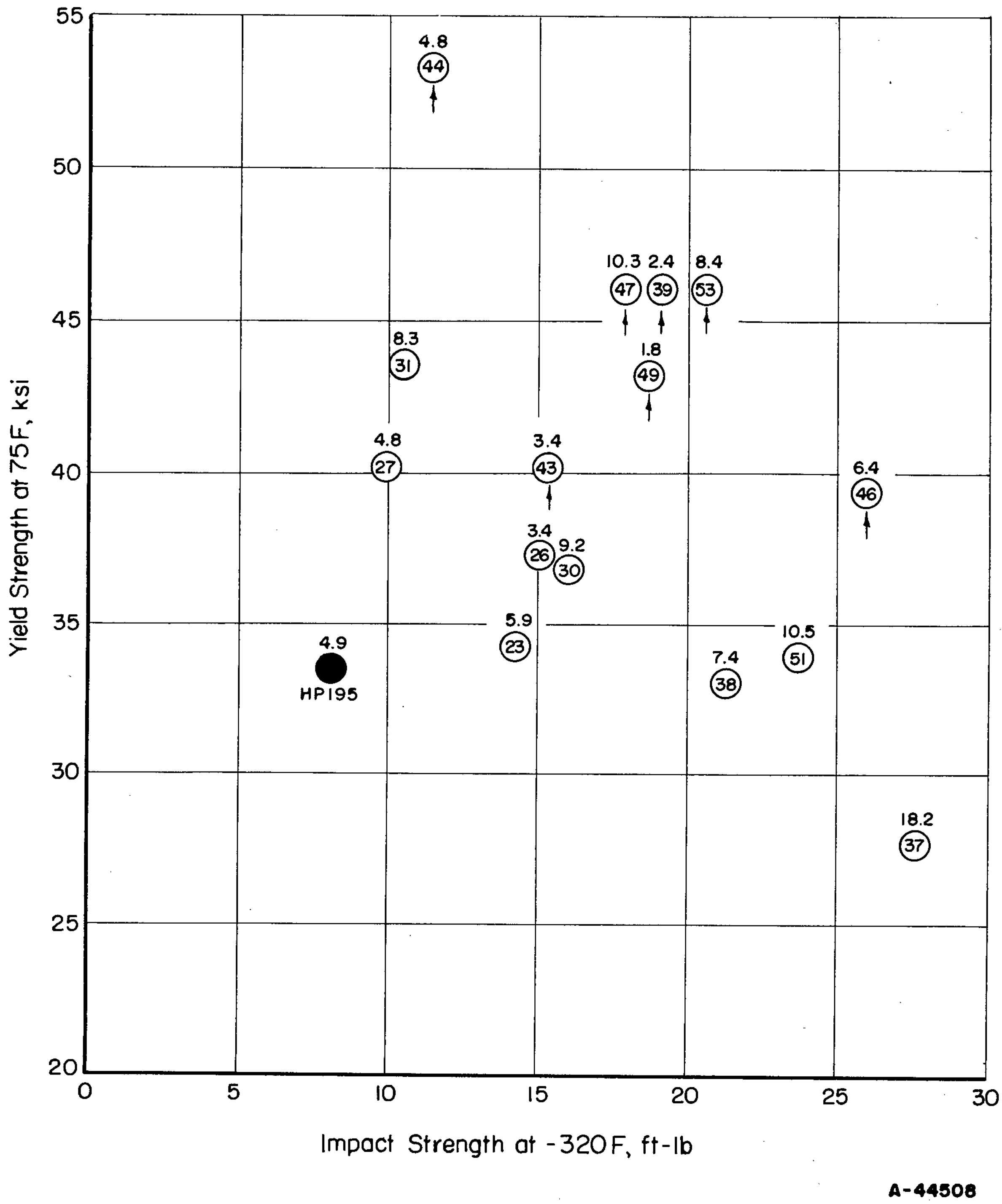
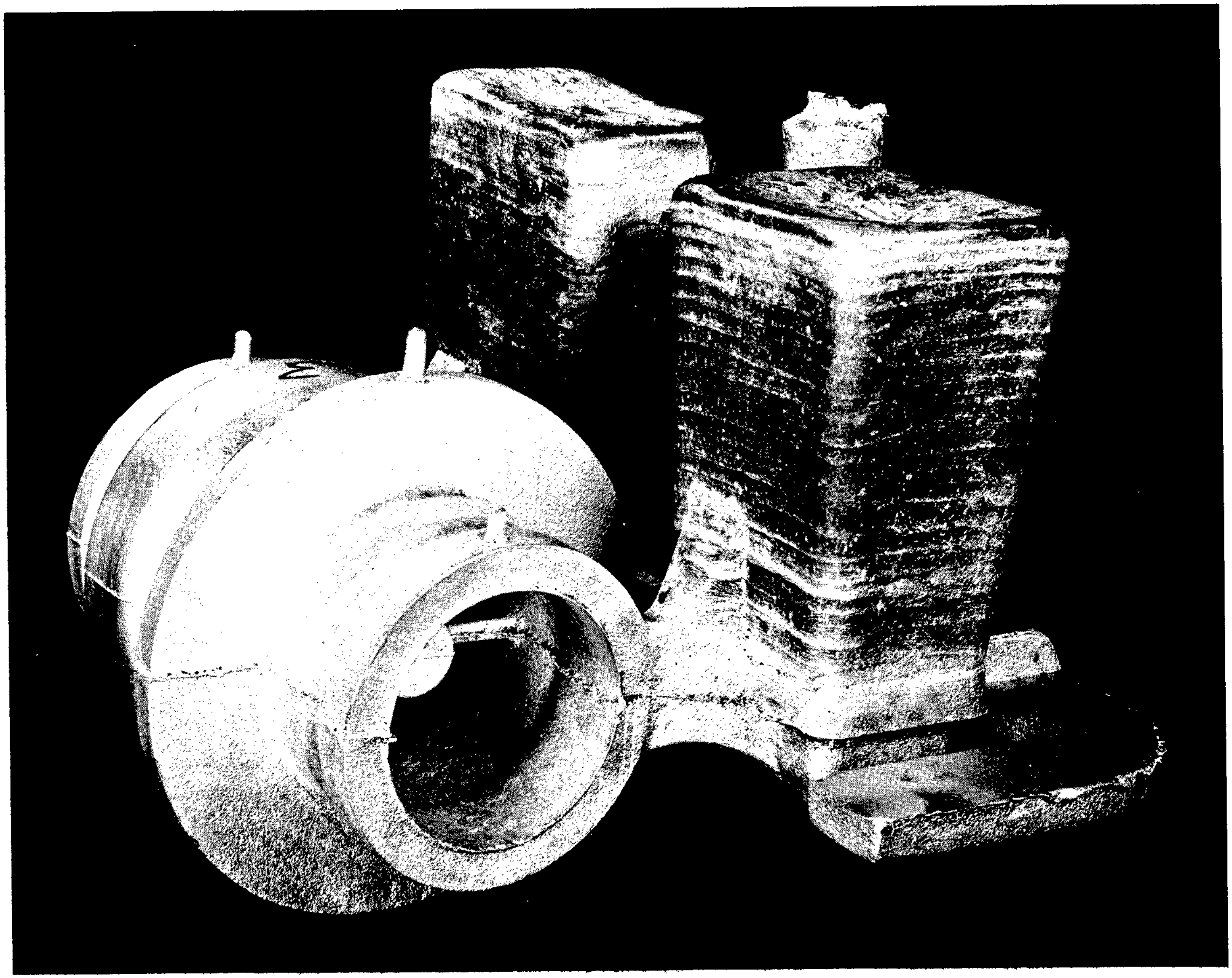


FIGURE 8. VARIATION OF IMPACT PROPERTIES AT -320 F WITH YIELD STRENGTH AT 75 F IN SEVERAL BOOK-MOLD CASTINGS

Alloy number is given inside circle and tensile ductility is indicated above. Arrow under point indicates that alloy contains cadmium.



N98033

FIGURE 9. PUMP-HOUSE CASTING

Approximate weight of casting, 17 pounds.

In addition to casting the three improved high-purity compositions, castings were made from the high-purity 195 alloy. High-purity 195 was the optimum composition resulting from the first year of research[1], and these castings were intended to serve as a basis for comparison with castings of the improved alloy compositions.

A small amount of surplus metal from the various alloy heats was cast into 1-1/4 x 8 x 10-inch iron book molds to provide data for correlation with that obtained in the alloy screening program.

Preparation of Castings

A total of sixteen melts were prepared in obtaining the castings required for the scale-up program. The complete melting records for these alloys are given in the Appendix, Table A-1. These procedures are summarized in Table 35. The alloys were cast into core-sand molds. Keel-block castings of the type shown in Figure 2 were made, as was the pump-house casting shown in Figure 9. The Al-Ti, Al-Cr, Al-Cu, and Al-Si master alloy used are described in the Appendix, Table A-2. Magnesium and cadmium were alloyed as elemental metal.* Special precautions were used to minimize contamination during melting, including the use of silicon carbide crucibles and graphite melting tools. A 10-minute chlorine gas fluxing period was used to remove hydrogen prior to casting, and the melts were held 10 minutes before casting to minimize oxide inclusions. A summary of the castings made in this program is given in Table 36.

Considerable difficulty was encountered in casting the pump housing. Problems were chiefly of three types: (1) excessive shrinkage porosity, and occasionally hot tearing, near the base of the flange radius adjacent to the boss, (2) hot tearing of the spider ribs inside the casting at the base of the internal heavy section, and (3) misfills of portions of the thin-walled section of maximum radius. A number of casting changes were made in an effort to overcome these problems. These are described in Table 37.

The first castings made, those of Alloys 54, 55, 56, 58, and 59, were cast by following normal practice. A standard core-sand mix was prepared, and molds were made from the pattern as received from NASA, but mounted on a match plate. Two gates fed through risers into the heavy end-ring sections located at both ends of the casting. The gates entered at the edge of the rings. Pouring was normally started at about 1400 F. Shrinkage was quite heavy along a portion of the flange radius of all the castings. To offset this problem the pattern was modified by increasing the radius along this side of the flange. As an additional aid in eliminating shrinkage in this region, a third gate was opened from the adjacent riser into the heavy boss which is part of the flange near the shrinkage area. Several of the castings also showed hot tearing in the spider ribs inside the casting. A softer core material was examined to minimize this problem and to facilitate removal of the core. Commercially, a shell-mold core probably would be used to minimize the spider rib shrinkage problem. Sand wash was also a problem in these castings which was compensated for by using a lower baking temperature on the sand and applying a mold spray to hold the sand more firmly.

All of the above changes were used in preparing molds for Alloys 62 and 63. However, the third gate into the boss in the four castings of Alloy 62 was small compared

*Special Note: Cadmium vapors are highly toxic. Adequate ventilation is mandatory during alloying. Respiratory masks for workmen are also recommended.

TABLE 35. OUTLINE OF MELTING PROCEDURES

Alloys 58, 59, 65, 4.5Cu-0.8Si	Alloys 54, 55, 66, 4.5Cu-0.25 Mg-0.1Ti	Alloys 56, 57, 64, 4.5Cu-0.1Cd-0.1Mg-0.05Ti	Alloys 60, 61, 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg
Melt aluminum	Melt aluminum	Melt aluminum	Melt aluminum
Add Al-20Cu master Add Al-12Si master	Add Al-20Cu master Add Al-6Ti master	Add Al-20Cu master Add Al-6Ti master Add cadmium	Add Al-20Cu master Add zinc Add cadmium Add Al-10Cr master
Chlorinate 10 minutes	Chlorinate 10 minutes Add magnesium	Chlorinate 10 minutes Add magnesium	Chlorinate 10 minutes Add magnesium
Hold 10 minutes	Hold 10 minutes	Hold 10 minutes	Hold 10 minutes
Cast	Cast	Cast	Cast

Note: Alloy 62 was prepared by remelting scrap from Heats 58 and 59
Alloy 63 was prepared by remelting scrap from Heats 58, 59, and 62
Alloy 67 was prepared by remelting scrap from Heats 54, 55, and 66
Alloy 68 was prepared by remelting scrap from Heats 56, 57, and 64
Alloy 69 was prepared by remelting scrap from Heats 60 and 61.

All scrap heats were chlorinated before casting, and small amounts (~0.1 per cent) of magnesium were added if the alloy composition contained magnesium.

TABLE 36. HIGH-PURITY CASTINGS PREPARED IN SCALE-UP PROGRAM

Alloy Composition	Alloy	Number of Sand Castings: Keel Blocks	Number of Sand Castings: Pump Housings	Number of Book-Mold Castings
4.5Cu-0.8Si	58	0	3	1
	59	0	3	1
	62	0	4	0
	63	0	2	0
	65	0	3	1
4.5Cu-0.25Mg-0.1Ti	54	1	2	1
	55	1	2	1
	66	1	3	0
	67	2	1	1
4.5 Cu-0.1Cd-0.1Mg-0.05Ti	56	1	2	1
	57	1	2	1
	64	1	2	1
	68	2	0	1
4.5 Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	60	1	2	1
	61	1	2	1
	69	2	0	1

TABLE 37. VARIABLES IN PUMP-HOUSE CASTINGS

Alloy	Casting[a]	Pattern Modification[b]	Gating System[c]	Mold Sand[d]	Core Sand[e]	Casting Temp, F	Problems Encountered
			4.5Cu-0.8Si				
58	1	None	1	R	R	1400	Considerable shrink
	2	"	"	"	"	1395	Ditto
	3	"	"	"	"	1390	"
59	1	"	"	"	"	1400	"
	2	"	"	"	"	1395	"
	3	"	"	"	"	1390	"
62	1	Modified	2	M	UF-1	1375	"
	2	"	"	"	M	1370	"
	3	"	"	"	UF-1	1325	Moderate shrink
	4	"	"	"	M	1320	Ditto
63	1	"	3	"	UF-1	1275	Good casting[f]
	2	"	"	"	"	1270	Ditto
65	1	"	"	"	"	1300	Misfill
	2	"	"	"	"	1290	Good casting
	3	"	"	"	UF-2	1280	Good casting
			4.5Cu-0.25Mg-0.1Ti				
54	1	None	1	R	R	1350	Considerable shrink
	3	"	"	"	"	1340	Slight shrink
55	1	"	"	"	"	1400	Considerable shrink
	3	"	"	"	"	1390	Ditto
66	2	Modified	3	M	UF-2	1340	Misfill
	3	"	"	"	"	1335	Good casting
	4	"	"	"	M	1330	Ditto
67	2	"	"	"	"	1340	
			4.5Cu-0.1Cd-0.1Mg-0.05Ti				
56	1	None	1	R	R	1420	Considerable shrink
	3	"	"	"	"	1410	Ditto
57	2	Modified	3	M	UF-1	1290	Good casting
	3	"	"	"	"	1280	Misfill
64	1	"	"	"	UF-2	1340	Good casting
	3	"	"	"	UF-1	1320	Ditto
			4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr				
60	1	Modified	3	M	UF-2	1330	Good casting
	3	"	"	"	"	1330	Ditto
61	1	"	"	"	"	1285	"
	3	"	"	"	"	1275	"

Footnotes appear on the following page.

Footnotes to Table 37.

(a) Missing numbers are keel block castings.

(b) Pattern modification consisted of increasing the fillet size between the flange and the thin wall section of the pump housing.

(c) Three gating systems were tried. These are designated as follows:
  (1) Two equal size gates into the heavy ends of the casting.
  (2) Three gates, with the third gate into the boss on the flange. This gate and the gate into the closer end were smaller than the third gate.
  (3) Three gates, with the gate into the boss considerably enlarged.

(d) Two types of molding sand were used. These are designated as regular (R) which corresponds to that described in Footnote (e), Table A-1, and modified (M), which corresponds to Footnote (g), Table A-1. The modifications were intended to reduce sand wash.

(e) Four types of core sands were used: Regular (R) or modified (M) sands, as described in Footnotes (e) and (h) of Table A-1; urea formaldehyde, soft (UF-1), described in Footnote (i), Table A-1; and urea formaldehyde, medium (UF-2), as described in Footnote (j), Table A-1. Core modifications were intended chiefly to facilitate removal.

(f) Although these castings were considered satisfactory, a core shift occurred which resulted in the wall thickness being heavy on the cope side.

with the same gate in the Alloy 63 castings. The small size third gate in castings of Alloy 62 tended to relieve the shrinkage problem but not to the same extent as the larger size third gate did in casting Alloy 63. These alloys also were cast at lower temperatures, and it was found that the casting problems were overcome with a combination of a large third gate and lower casting temperature. It seems probable that casting temperature was the most influential factor in improving casting quality. The remaining alloys, 57, 60, 61, 64, 65, 66, and 67, were made by following the practice devised above with generally good results. Misfills became more prevalent with lower casting temperatures, and this problem was not completely eliminated. It appears related to both fluctuation in melt temperature and trapped air caused by the lower mold permeability after using the Paraspray mold wash to prevent sand drag.

Preliminary chemical analysis results suggested that the copper content of some of the alloys was somewhat higher than desired. Therefore, three alloys were made with slight reductions in copper content, Alloys 67 through 69. The bulk of these was poured into keel-block castings, but one pump-house casting was made from Alloy 67.

Keel-block castings were prepared from all of the new alloy compositions. All castings except of Alloys 67, 68, and 69 were sectioned into test bar blanks as shown in Figure 3 and heat treated as follows:

980 F for 16 hours and quench in water at 150 F
325 F for 16 hours and air cool.

This treatment was selected on the basis of prior work with book-mold castings. Book-mold castings from these heats were sectioned as shown in Figure 7 and given a similar heat treatment.

Preliminary tests results on samples from keel-block and book-mold castings of Alloys 54 through 57 were quite disappointing. The fractured test samples appeared to contain internal defects, which showed up as dark areas on the fracture surface. It was thought that inadequate solution heat treatment may have contributed to the low properties. Therefore, a number of untested but machined samples from these alloys, as well as the sample blanks from Alloys 58 through 66, were solution annealed at 1000 F. Most of these samples were annealed for 40 hours. A portion were solution annealed for 24 hours in a furnace containing a small amount of Stauffer A-1 Protective Compound, since the defects resembled those encountered from sulfur contamination. During the removal of the test blanks from the quenching tank following heat treatment, a faint odor, tentatively identified as H_2S, was noticed in some of the heat treatments. However, since most of the material had already been heat treated at 980 F, if sulfur contamination was the cause of the poor properties, reheat treatment would not be expected to be beneficial. In this case, the compound could act only to prevent further damage. Keel-block castings and book-mold castings from Alloys 67 through 69 were heat treated at 1000 F only.

Book-mold castings from HP 195 Alloys 58 and 59 were heat treated as follows:

960 F for 16 hours and quench in water at 150 F
5 hours at 310 F.

The properties of these samples were also lower than expected. Material from the other HP 195 heats was therefore solution heat treated for 24 hours at 970 F to promote more complete solution of the Al-Cu phase.

Pump-house castings were examined at Battelle, using sample blanks cut from the flange section of the casting as shown in Figure 10. These blanks were heat treated and then machined to give Charpy impact samples or 0.25-inch-diameter tensile samples. Only a limited number of tests on pump-house castings were made at Battelle. Three pump-house castings of each alloy composition were heat treated to the T6 temper and sent to NASA for a more thorough study of the properties of the castings. These castings are described in Table 38, which includes the heat treatment procedures for each casting.

TABLE 38. PUMP-HOUSE CASTINGS SENT TO NASA

Melt	Casting	Nominal Composition	Heat Treatment
63	1	4.5Cu-0.8Si	24 hr 970 F, water quenched; 5 hr 310 F, air cool[(a)]
65	2	4.5Cu-0.8Si	Ditto
65	3	4.5Cu-0.8Si	"
54	3	4.5Cu-0.25Mg-0.1Ti	40 hr 1000 F, water quenched; 16 hr 325 F, air cool
66	4	4.5Cu-0.25Mg-0.1Ti	24 hr 1000 F, water quenched; 16 hr 325 F, air cool[(a)]
67	2	4.5Cu-0.25Mg-0.1Ti	Ditto
57	2	4.5Cu-0.1Cd-0.1Mg-0.05Ti	24 hr 1000 F, water quenched; 16 hr 325 F, air cool[(a)]
64	1	4.5Cu-0.1Cd-0.1Mg-0.05Ti	Ditto
64	3	4.5Cu-0.1Cd-0.1Mg-0.05Ti	40 hr 1000 F, water quenched; 16 hr 325 F, air cool
60	1	4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr	40 hr 1000 F, water quenched; 16 hr 325 F, air cool
61	1	4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr	Ditto
61	3	4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr	"

Note: All castings were quenched in water at 150 F after solution annealing.
(a) Heat treated in atmosphere of Stauffer A-1 Protective Compound.

Evaluation of Castings

Chemical Analysis

The results of spectrographic analyses of each of the 16 alloys prepared in the scale-up program are given in Table 39. An examination of these data shows that the copper content was higher than desired in a number of the alloys. At least part of the difficulty in adequately solution heat treating these castings can be attributed to this source. Silicon control was excellent in the 4.5Cu-0.8Si alloys.* Magnesium tended to fluctuate more widely and was higher than desired in Alloys 66 and 67. Cadmium and chromium retentions were quite good. Titanium retention was also good except in the case of Alloys 56 and 57. Iron control was excellent.

Alloy 66 is certainly too highly alloyed for optimum properties, and Alloys 54, 55, 56, and 57 are also appreciably higher in copper than is desirable.

*More recent analysis of the pump-house casting 57-2 by NASA gave a copper content of 3.96 per cent instead of 5.36 per cent. The high copper contents listed in Table 39 are therefore subject to some skepticism.

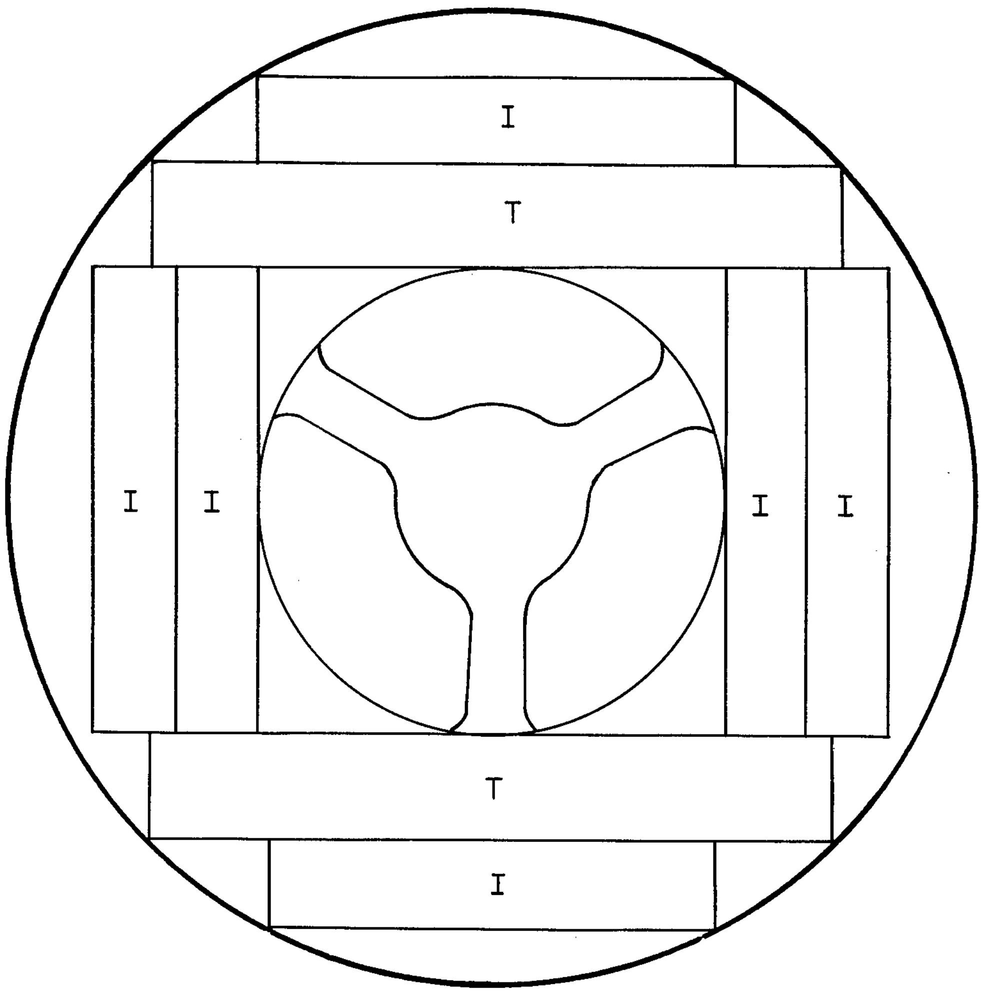


FIGURE 10. SECTIONING PROCEDURE FOR FLANGE SECTION OF PUMP HOUSE CASTING

T = tensile blank. I = impact blank.

TABLE 39. COMPOSITION OF SCALE-UP ALLOYS

Alloy	Composition, weight per cent								
	Si	Fe	Cu	Zn	Mg	Mn	Cr	Ti	Cd
				4.5 Cu-0.8Si (HP 195)					
58	0.79	<0.01	4.71	<0.01	<0.005	<0.005	<0.005	<0.01	<0.01
59	0.77	<0.01	4.70	<0.01	<0.005	<0.005	<0.005	<0.01	<0.01
62	0.81	<0.01	4.76	<0.01	<0.005	<0.005	<0.005	<0.01	<0.01
63	0.77	<0.01	4.73	<0.01	<0.005	<0.005	<0.005	<0.01	<0.01
65	0.72	<0.01	4.48	<0.01	<0.005	<0.005	<0.005	<0.01	<0.01
				4.5Cu-0.25Mg-0.1Ti					
54	0.01	0.01	4.90	<0.01	0.23	<0.005	<0.005	0.12	<0.01
55	0.01	0.01	5.30	<0.01	0.23	<0.005	<0.005	0.12	<0.01
66	<0.01	<0.01	6.68	<0.01	0.32	<0.005	<0.005	0.11	<0.01
67	<0.01	<0.01	4.58	<0.01	0.32	<0.005	<0.005	0.11	<0.01
				4.5Cu-0.1Cd-0.1Mg-0.05Ti					
56	0.01	<0.01	5.26	<0.01	0.10	<0.005	<0.005	<0.01	0.10
57	0.01	<0.01	5.36	<0.01	0.10	<0.005	<0.005	<0.01	0.10
64	<0.01	<0.01	4.20	<0.01	0.06	<0.005	<0.005	0.034	0.09
68	<0.01	<0.01	3.81	<0.01	0.09	<0.005	<0.005	0.043	0.08
				4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg					
60	<0.01	<0.01	3.92	1.96	0.11	<0.005	0.084	<0.01	0.12
61	<0.01	<0.01	3.93	2.02	0.11	<0.005	0.083	<0.01	0.12
69	<0.01	<0.01	3.89	2.02	0.12	<0.005	0.080	<0.01	0.08

Properties of Book-Mold Castings

The effect of the composition variations can be examined most readily by comparing the properties of book-mold castings. These data are given in Table 40, along with the expected properties based on data obtained from the screening program.

The 4.5Al-0.8Si alloys appear to be comparable to previously cast alloys. However, the comparison of book-mold properties must be made with the properties of sand castings.

No book-mold casting was made of Alloy 66, so the most highly alloyed 4.5Cu-0.25Mg-0.1Ti alloy is not represented in Table 40. However, it is apparent

TABLE 40. PROPERTIES OF HIGH-PURITY BOOK-MOLD CASTINGS IN THE T6 TEMPER

Alloy	Heat Treatment(a)	Unnotched Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Charpy Impact Properties at 75 F, ft-lb: 1	2	3	Average
			4.5Cu-0.8Si (HP 195)						
58	(1)	40.6	30.1	5.6	6.6	7.2	11.7	--	9.4
59	(1)	40.6	29.4	5.4	7.4	10.0	12.1	--	11.0
65	(5)	39.6	24.6	9.5	11.1	31.0	31.0	25.0	29.0(b)
65	(5)	43.9	27.0	11.0	11.7	--	--	--	--
	Average	41.2	27.8	7.9	9.2				10.2
	Sand Cast	44.6	30.2	7.5	9.9				8.4
			4.5Cu-0.25Mg-0.1Ti						
54	(2)	--	--	--	--	6.1	8.2	--	7.2
	(2) + (3)	51.9	43.4	3.9	6.6	11.4	15.0	--	13.2(c)
	(2) + (4)	59.9	44.4	7.8	10.4	--	--	--	--
55	(2)	--	--	--	--	3.8	6.0	--	4.9
	(2) + (3)	--	--	--	--	9.6	6.0	--	7.8
67	(3)	53.5	43.6	5.5	11.9	7.0	10.2	--	8.6
	Average	55.1	43.8	5.7	9.6				8.3
	Screening program(d)	54.3	39.4	8.9	11.2				11.5
			4.5Cu-0.1Cd-0.1Mg-0.05Ti						
56	(2)	--	--	--	--	4.0	4.6	--	4.3
	(2) + (3)	--	--	--	--	9.6	--	--	9.6
57	(2)	--	--	--	--	14.5	13.2	--	13.8
	(2) + (3)	51.4	44.0	5.1	9.7	25.0	19.3	--	22.2
	(2) + (4)	54.2	45.4	2.9	2.7	--	--	--	--
64	(2) + (3)	53.3	45.7	5.0	10.4	--	--	--	--
	(2) + (4)	--	--	--	--	15.5	14.0	--	14.8
68	(3)	51.7	43.6	6.0	11.2	15.6	16.6	20.8	17.6
	(4)	--	--	--	--	13.0	--	--	13.0
	Average	52.6	44.7	4.8	8.5				13.6
	Screening program(d)	50.9	42.6	8.4	10.1				16.5

Table 40. (Continued)

Alloy	Heat Treatment(a)	Unnotched Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Charpy Impact Properties at 75 F, ft-lb: 1	2	3	Average
			4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr						
60	(2) + (3)	53.4	45.4	3.2	11.5	--	--	--	--
	(2) + (4)	--	--	--	--	19.2	7.0	--	13.2
61	(2) + (3)	53.9	--	--	4.6	--	--	--	--
	(2) + (4)	--	--	--	--	19.5	13.1	--	16.3
69	(3)	52.8	45.8	2.8	6.7	14.0	21.5	--	17.8
	Average	53.4	45.6	3.0	7.6				15.8
	Screening program	51.0	46.0	8.4	10.9				18.7

(a) (1) 16 hours at 960 F, quenched; 5 hours at 310 F
(2) 16 hours at 980 F, quenched; 16 hours at 325 F
(3) 40 hours at 1000 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched; 16 hours at 325 F (Stauffer A-1 Protective Compound in furnace)
(5) 24 hours at 970 F, quenched; 5 hours at 310 F.

(b) This value seems unreasonably high based on prior work on this alloy. A machine-setting error may have occurred. It has been omitted from the average value for this alloy.

(c) These impact samples given a triple heat treatment (2) + (16 hours at 960 F, quench, 16 hours at 325 F) + (3).

(d) Extrapolated from properties of alloys of similar composition.

that Alloy 55 (5.3Cu) is inferior in toughness to Alloy 54 (4.9Cu) even after heat treatment at 1000 F. It also appears that the higher magnesium content in Alloy 67 is detrimental to toughness and tensile ductility. None of these alloys was as good as had been anticipated from the results obtained in the scale-up program.

A limited amount of book-mold data is available from all four of the 4.5Cu-0.1Cd-0.1Mg-0.05Ti melts (Table 40). Again, none of the alloys was as good as expected on the basis of the results of the screening program. The variation in copper content does not correlate too well with the variation in toughness observed in this group of alloys. This composition appears capable of absorbing quite wide composition fluctuations without damage to properties. The higher temperature solution heat treatment appeared to benefit both Alloy 56 and Alloy 57.

Data from book-mold castings is also available from all three melts of the 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg alloy. These three alloys, as shown in Table 39, were quite similar in composition. They also show similar tensile and impact properties. However, tensile ductility is much lower than anticipated from the alloy-screening program. No reason for this difference is readily apparent, although it should be noted that these alloys were cast at a lower temperature, 1350 to 1285 F as compared with 1400 F in the screening program.

Although the book-mold test data in Table 40 are not greatly different from that expected from the alloy-screening program, it does appear that significant differences in tensile ductility exist between the screening-alloy book-mold castings and the scale-up-alloy book-mold castings. No cause for this difference could be identified.

Properties of Keel-Block Castings

The unnotched tensile properties of the three new alloys as measured from keel-block castings are given in Table 41. Impact properties are given in Table 42. Although all of these samples were heat treated at 1000 F, a number were given a prior heat treatment at 980 F. Where comparisons are possible, no clear-cut effect of the prior heat treatment at 980 F is apparent. Therefore, the data have been averaged for presentation in Table 43 without consideration of heat treatment.

The toughest of the 4.5Cu-0.25Mg-0.1Ti castings was Alloy 54, with Alloy 67 being next best. This difference appears related to composition, Alloy 54 containing somewhat more copper and less magnesium than did Alloy 67. Tensile ductility was low in both castings, however. Small internal defects were frequently seen on the fracture surface, appearing as dark patches in the otherwise bright fracture area. Impact properties were not greatly affected by temperature of testing, but tensile ductility was reduced at -420 F in Alloy 54 and at -320 F in Alloy 67. The 4.5Cu-0.25Mg-0.1Ti alloy had much better yield strength than HP 195 alloy, but its toughness was about the same, and its tensile ductility was lower. The loss in ductility at low temperature observed in this alloy must also be considered an unfavorable characteristic.

TABLE 41. TENSILE PROPERTIES OF HIGH-PURITY KEEL-BLOCK CASTINGS IN THE T6 TEMPER

Alloy	Heat Treatment(a)	Test Temperature, F	Unnotched Tensile Properties: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Modulus of Elasticity, 10^6 psi
			4.5Cu-0.25Mg-0.1Ti				
54	(2) + (4)	75	42.9	40.7	2.0	1.1	9.2
	(2) + (4)	75	40.0	--	1.1	1.1	--
	(2) + (4)	-320	53.9	49.0	3.5	3.9	10.5
	(2) + (4)	-320	54.4	48.1	4.0	3.6	11.0
	(2) + (4)	-420(b)	58.1	58.1	<1.0	--	--
55	No data	--	--	--	--	--	--
66	(2) + (3)	75	37.4	--	2.0	2.0	--
67	(3)	75	44.9	41.7	2.5	3.5	9.7
	(4)	75	47.3	42.9	2.8	2.7	9.1
	(3)	-320	37.0	--	1.2	1.6	11.0
			4.5Cu-0.1Cd-0.1Mg-0.05Ti				
56	No data	--	--	--	--	--	--
57	(2) + (4)	75	47.4	46.0	2.2	1.9	10.2
	(2) + (4)	-320	57.4	54.4	3.2	5.9	11.1
	(2) + (4)	-320	61.0	57.9	3.2	5.1	12.0
	(2) + (4)	-420(b)	70.9	67.4	4.0	--	--
64	(2) + (3)	75	47.7	44.9	2.5	3.9	10.7
	(2) + (4)	75	49.4	45.1	2.0	1.9	9.8
68	(3)	75	43.9	42.4	3.0	5.8	10.5
	(4)	75	48.1	44.1	3.5	3.1	9.4
	(4)	-320	57.4	50.2	6.0	9.3	11.1
			4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg				
60	(2) + (3)	75	33.1	--	1.5	--	--
61	(2) + (3)	75	16.2	--	1.2	1.0	--
	(2) + (3)	75	33.9	--	1.2	1.0	--
69	(3)	75	13.6	--	1.0	0.8	--

(a) (2) 16 hours at 980 F, quenched; 16 hours at 325 F
(3) 40 hours at 1000 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched, 16 hours at 325 F (Stauffer A-1 protective compound in furnace).
(b) Tests at -420 F conducted by NASA.

TABLE 42. IMPACT PROPERTIES OF HIGH-PURITY KEEL-BLOCK CASTINGS IN THE T6 TEMPER

Alloy	Heat Treatment[a]	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	4	Average
		4.5Cu-0.25Mg-0.1Ti					
54	(2) + (3)[b]	75	6.1	8.3	8.0	--	7.5
	(2) + (4)	75	7.0	6.9	--	--	7.0
	(2) + (4)	-100	8.3	10.5	8.0	7.0	8.6
	(2) + (4)	-320	7.8	8.5	11.2	11.0	9.6
	(2) + (4)	-420[c]	8.0	10.5	8.8	8.5	8.9
55	(2) + (3)	75	6.0	5.2	7.8	5.9	6.2
66	(2) + (3)	75	3.5	3.2	--	--	3.4
67	(3)	75	5.2	5.0	--	--	5.1
	(4)	75	7.1	5.0	--	--	6.0
	(4)	-320	7.1	8.5	--	--	7.8
	(4)	-420[c]	7.0	7.5	--	--	7.2
		4.5Cu-0.1Cd-0.1Mg-0.05Ti					
56	(2) + (3)	75	3.2	6.2	4.9	--	4.8
57	(2) + (3)	75	16.0	12.0	14.0	--	14.0
	(2) + (4)	75	13.2	--	--	--	13.2
	(2) + (4)	-100	16.5	10.0	--	--	13.2
	(2) + (4)	-320	12.0	16.5	--	--	14.2
	(2) + (4)	-420[c]	19.5	27.3	--	--	23.4
64	(2) + (3)	75	14.0	15.0	--	--	14.5
	(2) + (4)	-320	16.5	16.3	--	--	16.4
68	(3)	75	13.8	7.5	--	--	10.6
	(4)	75	13.0	14.0	--	--	13.5
	(4)	-100	12.3	12.8	--	--	12.6
	(4)	-320	19.0	20.0	--	--	19.5
	(4)	-420[c]	21.5	21.5	--	--	21.5
		4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg					
60	(2) + (4)	75	5.8	6.5	--	--	6.2
61	(2) + (3)	75	5.5	--	--	--	5.5
	(2) + (4)	75	7.0	6.2	--	--	6.6
69	(3)	75	5.0	3.5	--	--	4.2

(a) (2) 16 hours at 980 F, quenched; 16 hours at 325 F
(3) 40 hours at 1000 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched; 16 hours at 325 F (Stauffer A-1 protective compound in furnace).
(b) These impact samples given a triple heat treatment (2) + (16 hours at 960 F, quench; 16 hours at 325 F) + (3).
(c) Tests at -420 F performed by NASA.

TABLE 43. PROPERTIES OF HIGH-PURITY KEEL-BLOCK CASTINGS IN THE T6 TEMPER

Alloy	Test Temperature, F	Unnotched Tensile Properties: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Charpy Impact Properties, ft-lb
			4.5Cu-0.25Mg-0.1Ti			
54	75	41.4	40.7	1.6	1.1	7.2
	-100	--	--	--	--	8.4
	-320	54.2	48.6	3.8	3.8	9.6
	-420	58.1	58.1	<1.0	--	8.9
55	75	--	--	--	--	6.2
66	75	37.4	--	2.0	2.0	3.4
67	75	46.1	42.3	2.6	3.1	5.6
	-320	37.0	--	1.2	1.6	7.8
	-420	--	--	--	--	7.2
			4.5Cu-0.1Cd-0.1Mg-0.05Ti			
56	75	--	--	--	--	4.8
57	75	47.4	46.0	2.2	1.9	13.6
	-100	--	--	--	--	13.2
	-320	59.2	56.2	3.2	5.5	14.2
	-420	70.9	67.4	4.0	--	23.4
64	75	48.6	45.0	2.2	2.9	14.5
	-320	--	--	--	--	16.4
68	75	46.0	43.2	3.2	4.4	12.0
	-100	--	--	--	--	12.6
	-320	57.4	50.2	6.0	9.3	19.5
	-420	--	--	--	--	21.5
			4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg			
60	75	33.1	--	1.5	--	6.2
61	75	20.0	--	1.2	1.0	6.0
69	75	13.6	--	1.0	0.8	4.2

All of the 4.5Al-0.1Cd-0.1Mg-0.05Ti alloys were quite tough except Alloy 56. Since the copper content of Alloy 56 was lower than that of Alloy 57, this lesser toughness does not appear related to composition. The remaining three alloys showed comparable properties, despite a significant difference in composition. Tensile ductility was low but did not appear to decrease as temperature decreased. Impact toughness increased quite markedly with decreased temperature. Yield strength was high in this composition. It is definitely the best of the three new alloy compositions examined in the scale-up program. Defects in the fracture surface were not observed too frequently, but were present.

All three of the 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg alloy keel-block castings were extremely brittle and had rather low toughness. This alloy was quite coarse grained as cast. Grain boundaries were readily visible on the bar surface after heat treatment, suggesting severe attack of grain boundaries during heat treatment. Defect areas often occupied over half of the fracture surface of broken test samples and were present in almost all samples. The poor properties of the keel-block castings in this alloy appear to be related to large grain size and to heavy attack during heat treatment. Metallographic examination of cast material suggested that the defects present after heat treatment were introduced during heat treatment. However, it was not possible to locate the source of damage or to eliminate it by changes in the heat-treatment schedule or by using a protective compound in the furnace. It is possible that the defect resulted from grain-boundary melting of cadmium, which may have been present in larger amounts in this alloy than in the alloy examined in the screening program. However, the defects which were observed in this alloy were also noted to a lesser extent in the other two alloys, including the cadmium-free alloy. The other two alloys had a much finer cast grain size, which may account for their lesser attack if damage was caused by grain-boundary attack during heat treatment.

Notched tensile properties at 75 and -320 F were determined for two of the castings of the 4.5Cu-0.1Cd-0.1Mg-0.05Ti composition. These data are shown in Table 44. Both castings showed excellent notch toughness, the notched:unnotched strength ratio with a stress concentration factor of 10 being greater than 1.5 at both 75 and -320 F.

TABLE 44. NOTCHED TENSILE PROPERTIES OF HIGH-PURITY KEEL-BLOCK CASTINGS OF 4.5Cu-0.1Cd-0.1Mg-0.05Ti ALLOY IN THE T6 TEMPER

Alloy	Heat Treatment[a]	Temperature, F	Notched Tensile Properties, k_t = 10: Strength, ksi	Notched Tensile Properties, k_t = 10: Reduction in Area, per cent	Notched:Unnotched Strength Ratio[b]
57	(2) + (4)	75	72.0	9.2	1.52
		-320	89.5	10.0	1.51
68	(3)	75	70.8	7.4	1.54
		-320	86.6	9.1	1.51

(a) (2) 16 hours at 980 F, quenched; 16 hours at 325 F
(3) 40 hours at 1000 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched; 16 hours at 325 F (Stauffer A-1 protective compound in furnace).

(b) Unnotched tensile data from Table 43.

Two of the heat-treated keel-block castings were welded with 2319 weld wire by using the techniques described previously. These data are shown in Table 45. Although the welds were ductile, the strength was low in both alloys.

TABLE 45. TENSILE PROPERTIES OF WELDED HIGH-PURITY KEEL-BLOCK CASTINGS

Alloy	Composition	Tensile Properties, As Welded				Modulus of Elasticity, 10^6 psi
		Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent	
64	4.5Cu-0.1Cd-0.1Mg-0.05Ti	26.1	16.6	3.2	5.9	11.3
61	4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	26.1	16.2	3.1	2.8	10.6

Properties of Pump-House Castings

Tensile and impact properties of several of the pump-house castings were measured at Battelle from samples cut from the flange, as shown in Figure 10. These data are given in Tables 46 and 47. Again, since heat treatment variations were small, the data have been summarized in Table 48. The testing of pump-house castings at Battelle was not extensive.

The HP 195 castings were low in tensile ductility but had good impact toughness. The properties of pump-house castings of two of the three new alloys, 4.5Cu-0.25Mg-0.1Ti and 4.5Cu-0.1Cd-0.1Mg-0.05Ti, were quite similar to those in the keel-block casting. The properties of the 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg alloy pump-house casting were much superior to those of the keel-block castings, however. Examination of the test bars showed that the defects present in the keel blocks occurred much more infrequently in the pump-house casting. This appears related to cast grain size, which tended to be smaller in the thinner section pump-house casting.

Twelve high-purity castings were sent to NASA in the heat-treated condition for evaluation. These castings, which are listed in Table 38, included three castings of each of the four high-purity alloys prepared in the scale-up program. The complete results of this evaluation are not yet available. Preliminary tensile and impact properties of each alloy are reported in Table 49. Each test value given in this table represents an average of a minimum of five tests, and the data are averaged by composition without regard to alloy number. The tensile ductility found in the tests by NASA was approximately 3 times that found in tests at Battelle, as can be seen by comparison of data in Table 49 with that in Table 48. This is probably due to the fact that the NASA castings were heat treated before sectioning such that a saw-cut surface was not exposed to the furnace atmosphere. Also, the NASA castings were heat treated late in the program, at which time it is probable that any contaminant in the furnace had been greatly reduced. A much better correlation exists between strength and impact properties obtained in tests at Battelle and in the screening and scale-up programs. However, in most cases the NASA castings showed somewhat superior properties.

TABLE 46. TENSILE PROPERTIES OF HIGH-PURITY PUMP-HOUSE CASTINGS IN THE T6 TEMPER

Alloy	Heat Treatment[a]	Unnotched Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction in Area, per cent
		4.5Cu-0.8Si (HP 195)			
59	(1)	26.2	26.1	2.0	3.7
	(1)	32.4	29.6	3.0	5.7
63	(5)	18.8	18.0	2.5	3.8
	(5)	38.9	28.9	3.0	6.9
65	(5)	28.4	24.5	4.0	7.7
	(5)	40.1	29.4	3.8	11.4
		4.5Cu-0.25Mg-0.1Ti			
54	(2) + (4)	44.5	38.8	2.0	3.0
66	(4)	49.1	42.9	1.0	3.7
		4.5Cu-0.1Cd-0.1Mg-0.05Ti			
56	(2)	35.6	--	1.0	2.0
57	(4)	52.6	50.9	3.0	6.4
		4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg			
60	(4)	53.4	51.7	3.0	7.1

(a) (1) 16 hours at 960 F, quenched; 5 hours at 310 F
(2) 16 hours at 980 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched; 16 hours at 325 F (Stauffer A-1 protective compound in furnace)
(5) 24 hours at 970 F, quenched; 5 hours at 310 F.

TABLE 47. IMPACT PROPERTIES OF HIGH-PURITY PUMP-HOUSE CASTINGS IN THE T6 TEMPER

Alloy	Heat Treatment(a)	Test Temperature, F	Charpy Impact Properties, ft-lb 1	2	3	Average
		4.5Cu-0.8Si (HP 195)				
63	(5)	75	7.0	9.0	11.9	9.3
	(5)	-320	6.0	8.8	9.0	7.9
65	(5)	75	14.0	14.0	10.8	12.9
	(5)	-320	14.0	11.5	19.0	14.7
		4.5Cu-0.25Mg-0.1Ti				
54	(2) + (3)	75	8.3	10.4		9.4
	(2) + (3)	-320	8.5	9.7		9.1
66	(3)	75	5.4	3.0		4.2
	(4)	-320	2.3	3.0		2.6
		4.5Cu-0.1Cd-0.1Mg-0.05Ti				
57	(2) + (3)	75	13.0	13.4		13.2
	(2) + (3)	-320	15.0			15.0
	(2) + (4)	-320	12.8			12.8
		4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg				
60	(3)	75	7.0	7.5		7.2
	(4)	75	6.8	6.1		6.4
	(4)	-320	11.2	7.0		9.1

(a) (2) 16 hours at 980 F, quenched; 16 hours at 325 F
(3) 40 hours at 1000 F, quenched; 16 hours at 325 F
(4) 24 hours at 1000 F, quenched; 16 hours at 325 F (Stauffer A-1 protective compound in furnace)
(5) 24 hours at 970 F, quenched; 5 hours at 310 F.

TABLE 48. PROPERTIES OF HIGH-PURITY PUMP-HOUSE CASTINGS IN THE T6 TEMPER

Alloy		Unnotched Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation, per cent	Reduction In Area, per cent	Charpy Impact Properties ft-lb: 75 F	-320
			4.5Cu-0.8Si (HP 195)				
59		29.3	27.8	2.5	4.7	--	--
63		28.8	23.4	2.8	5.4	9.3	7.9
65		34.2	27.0	3.9	9.6	12.9	14.7
	Average	30.8	26.1	3.1	6.2	11.1	11.3
			4.5Cu-0.25Mg-0.1Ti				
54		44.5	38.8	2.0	3.0	9.4	9.1
66		49.1	42.9	1.0	3.7	3.4	--
	Average	46.8	40.8	1.5	3.4	6.4	
			4.5Cu-0.1Cd-0.1Mg-0.05Ti				
56		35.6	--	1.0	2.0	--	--
57		52.6	50.9	3.0	6.4	13.2	13.9
			4.5Cu-2.0Zn-0.1Cd-0.1Mg-0.1Cr				
60		53.4	51.7	3.0	7.1	6.8	9.1

TABLE 49. AVERAGE MECHANICAL PROPERTIES OF HIGH-PURITY PUMP-HOUSE CASTINGS (T6 TEMPER) TESTED BY NASA[a]

Alloy Composition	Test Temperature, F	Unnotched Tensile Properties: Ultimate Strength, ksi	Unnotched Tensile Properties: Yield Strength, ksi	Unnotched Tensile Properties: Elongation, per cent	Charpy Impact Properties, ft-lb
4.5Cu-0.8Si (HP 195)	75	37.7	27.3	9.8	10.8
	-320	49.0	39.5	6.7	11.7
	-420	62.6	47.6	6.8	11.0
4.5Cu-0.25Mg-0.1Ti	75	47.2	42.9	3.7	4.5
	-320	56.0	52.2	3.4	6.7
	-420	68.0	57.7	4.5	6.9
4.5Cu-0.1Cd-0.1Mg-0.05Ti	75	47.7	44.7	5.0	13.6
	-320	56.6	52.4	6.4	18.6
	-420	70.6	56.9	9.4	15.5
4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	75	51.8	48.4	4.5	9.5
	-320	61.9	57.0	8.9	12.7
	-420	75.6	62.1	7.0	16.6

NASA performed pressure tests on one casting, 57-2, and found it to be free of leaks. This casting also had several 2219 lugs attached by welding without any apparent problems. Corrosion tests suggested that the zinc-containing alloy may be the most corrosion resistant.

Additional testing is under way to evaluate welding behavior and the properties of weldments.

Discussion of Results

The present study has shown that high-purity aluminum sand castings can be prepared which show impact toughness at -420 F in excess of 15 ft-lb, which have a yield strength at 75 F in excess of 40 ksi, which can have attachments made by welding, and which can be cast into intricate shapes. On the basis of test results now available, two compositions appear especially useful:

4.5Cu-0.1Cd-0.1Mg-0.05Ti
4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg.

The first alloy shows superior impact properties, but somewhat lower yield strength. Both alloys are significantly stronger and tougher than high-purity 195 alloy.

During the scale-up program, major problems were encountered in the heat-treating operations. Although the source of the trouble was not identified, some type

of attack of the metal during solution heat treatment is suspected. It is possible that sulfur was present in the furnace from prior work on magnesium. The zinc-containing alloy was most severely damaged, but all alloys, including HP 195, showed some evidence of damage. Damage was most severe in the keel-block castings and least severe in the book-mold castings. The pump-house castings heat treated without sectioning late in the program showed little evidence of damage. It appears that damage increased with increased grain size and when a saw-cut surface was exposed to the furnace atmosphere. Until the source of the problem is identified, it appears that extreme care should be exercised during heat treatment. The use of a protective compound in the furnace atmosphere did not show a clear-cut benefit, but seems to be a justifiable precaution.

A summary of the tensile and impact data obtained during the scale-up program is given in Table 50. If the data for HP 195 are examined, it is seen that ductility was low in only one casting, the pump-house casting sectioned before heat treatment. (The keel-block casting was prepared during the first year of research and does not show the low ductility observed in the material heat treated during the scale-up program.) It appears therefore that low ductility is not a result of sand casting as compared with book-mold casting, even though some increase in strength does appear attributable to this cause. In the three other alloys, which appeared to be more susceptible to damage during heat treatment than HP 195, ductility is significantly lower in the material prepared in the scale-up program than in the screening program. It seems reasonable to assume that in the absence of the heat-treating problems encountered in the scale-up program, tensile ductility of these three alloys would have exceeded 7 per cent in all of the castings. The low ductility does not appear to be an intrinsic property of the three new casting-alloy compositions.

Analysis of the impact data along similar lines suggests that two of the alloys, 4.5Cu-0.25Mg-0.1Ti and 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg, are capable of much higher impact properties than developed in the castings prepared during the scale-up program. The third alloy, 4.5Cu-0.1Cd-0.1Mg-0.05Ti, appeared to develop impact properties in the scale-up program only slightly lower than those which have been expected based on the data obtained during the screening program.

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SUMMARY AND CONCLUSIONS

A study of the effects of alloy composition on the properties of high-purity Al-Cu casting alloys has shown that it is possible to prepare castings with a yield strength at Al room temperature of 40 to 45 ksi and Charpy impact properties at -420 F of 15 ft-lb Al or more. Strength is obtained primarily through the addition of a small amount of cadmium. Al

The best alloy composition developed during this program was 4.5Cu-0.1Cd-0.1Mg-0.05Ti. A reasonably complex sand casting was made from this alloy without undue difficulty. Al The alloy must be heat treated to the T6 temper to develop optimum properties. Castings of this alloy can be joined by welding, Al using 2319 weld wire, but weldments do not develop strengths equivalent to that of the base alloy.

Al

A problem was encountered during heat treatment of several of the high-purity alloy compositions. Rather serious internal defects appeared to develop during heat treatment which affected tensile ductility quite noticeably. The source of this problem was not identified. It appeared to be more serious in castings having a large grain size

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TABLE 50. A SUMMARY OF THE PROPERTIES OF FOUR HIGH-PURITY CASTINGS IN THE T6 TEMPER

Description of Casting	Unnotched Tensile Properties at 75 F: Ultimate Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation per cent	Charpy Impact Properties, ft-lb: 75 F	-320 F
4.5Cu-0.8Si (HP 195)					
Book mold (scale-up program)	41.2	27.8	7.9	10.2	--
Pump house (NASA)	37.7	27.3	9.8	10.8	11.7
Pump house (Battelle)	34.2	26.1	3.1	11.2	11.3
Keel block[a]	44.6	30.2	7.5	8.4	8.0
4.5Cu-0.25Mg-0.1Ti					
Book mold (screening program)	54.3	39.4	8.9	11.4	13.6
Book mold (scale-up program)	55.1	43.8	5.7	8.3	--
Pump house (NASA)	47.2	42.9	3.7	4.5	6.7
Pump house (Battelle)	46.8	40.8	1.5	6.4	9.1
Keel block	41.6	41.5	2.1	5.8	8.7
4.5Cu-0.1Cd-0.1Mg-0.05Ti					
Book mold (screening program)	50.9	42.6	8.4	16.5	21.9
Book mold (scale-up program)	52.6	44.7	4.8	13.6	--
Pump house (NASA)	47.7	44.7	5.0	13.6	18.6
Pump house (Battelle)	52.6	50.9	3.0	13.2	13.9
Keel block	47.3	44.7	2.5	11.2	16.7
4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg					
Book mold (screening program)	51.0	46.0	8.4	18.7	20.4
Book mold (scale-up program)	53.4	45.6	3.0	15.8	--
Pump house (NASA)	51.8	48.4	4.5	9.5	12.7
Pump house (Battelle)	53.4	51.7	3.0	6.8	9.1
Keel block	22.2	--	1.2	5.4	--

(a) These data are from Alloy 12, 1962 Summary Report.(1)

or a machined surface exposed to the heat-treating atmosphere. The most likely explanation of the problem is that the furnace atmosphere had become contaminated with sulfur. Al

A second alloy developed in this program appears potentially superior in properties to the alloy listed above. The composition of this alloy was 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg. Cr This alloy tended to develop a large as-cast grain size and was much more severely damaged during heat treatment. However, if subsequent work should show that this problem is not related in any way to composition, this high-purity casting alloy may warrant commercial exploitation.

Although less easily cast into intricate shapes than A356, these two alloy compositions are sufficiently castable for many shapes. They appear comparable to 195 alloy in castability.

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APPENDIX A

TABULATED DATA

TABLE A-1. MELTING RECORDS, 60 TO 70-POUND MELTS

	Melt 17	Melt 18	Melt 19	Melt 20	Melt 21	Melt 22
Purpose of Melt	High-purity 5.5Cu	High-purity 6.5Zn-1.0Mg	High-purity 4.5Cu	High-purity 4.5Cu-0.8Si	High-purity 4.5Cu-0.8Si-0.6Fe	High-purity 4.5Cu-1.5Mg
Melting Date	Sept. 11, 1962	Sept. 11, 1962	Sept. 6, 1962	Sept. 6, 1962(b)	Sept. 7, 1962	Sept. 7, 1962
Alloy Charge	49.0 lb high-purity Al 19.2 lb Al-Cu master 1.8 lb Al-Ti master	63 lb high-purity Al 4.6 lb Zn 0.7 lb Mg 1.8 lb Al-Ti master	52.5 lb high-purity Al 15.8 lb Al-Cu master 1.8 lb Al-Ti master	47.6 lb high-purity Al 15.8 lb Al-Cu master 4.9 lb Al-Si master 1.8 lb Al-Ti master	46.8 lb high-purity Al 15.8 lb Al-Cu master 4.9 lb Al-Si master 0.8 lb Al-Fe master	51.4 lb high-purity Al 14.1 lb Al-Cu master 2.8 lb Cu-Ti master 0.1 lb Mg(c) 0.7 lb Al-Ti master
Crucible	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2
Time Molten	80 min	70 min	50 min	70 min	90 min	45 min
Chlorine Fluxing Time	15 min	15 min	10 min	10 min	10 min	10 min
Chlorine Fluxing Temp	1360 to 1500 F	1330 to 1475 F	1285 to 1410 F	1320 to 1610 F	1335 to 1435 F	1295 to 1415 F
Maximum Melt Temp	1500 F	1500 F	1410 F	1610 F	1615 F	1430 F
Casting Temperature	1400 F	1410 F	1400 F	1375 F	1415 F	1425 F
Melt Additions						
Alloying Elements	5.5Cu(Al-Cu master)	6.5Zn 1.0Mg	4.5Cu(Al-Cu master)	4.5Cu(Al-Cu master) 0.8Si(Al-Si master)	4.5Cu(Al-Cu master) 0.8Si(Al-Si master) 0.6Fe(Al-Fe master)	4.5Cu(Al-Cu + Cu-Ti master) 0.15Mg
Grain Refiners	0.15Ti(Al-Ti master)	0.15Ti(Al-Ti master)	0.15Ti(Al-Ti master)	0.15Ti(Al-Ti master)	0.15Ti(Al-Ti master)	0.15Ti(Al-Ti + Cu-Ti master)
Inoculant	None	None	None	None	None	None
Inhibitor	None	None	None	None	None	None
Moisture in Air	4.55 grains/ft^3	4.37 grains/ft^3	3.15 grains/ft^3	4.08 grains/ft^3	4.27 grains/ft^3	4.44 grains/ft^3
Molding Sand	(a)	(a)	(a)	(a)	(a)	(a)
Permeability	(d)	(d)	92	92	128	128
Green Strength	(d)	(d)	1.0	1.0	0.6	0.6

Footnotes appear at the end of this table.

TABLE A-1. (Continued)

	Melt 54	Melt 55	Melt 56	Melt 57	Melt 58	Melt 59
Purpose of Melt	High-purity 4.5Cu-0.25Mg-0.1Ti	High-purity 4.5Cu-0.25Mg-0.1Ti	High-purity 4.5Cu-0.1Cd-0.1Mg-0.05Ti	High-purity 4.5Cu-0.1Cd-0.1Mg-0.05Ti	High-purity 195	High-purity 195
Melting Date	April 4, 1963	April 4, 1963	April 4, 1963	April 15, 1963	March 27, 1963	March 27, 1963
Alloy Charge	49.2 lb high-purity Al 14.6 lb Al-Cu master 0.16 lb Mg 1.1 lb Al-Ti master	49.2 lb high-purity Al 14.6 lb Al-Cu master 0.16 lb Mg 1.1 lb Al-Ti master	49.7 lb high-purity Al 14.6 lb Al-Cu master 0.07 lb Cd 0.07 lb Mg 0.5 lb Al-Ti master	49.7 lb high-purity Al 14.6 lb Al-Cu master 0.07 lb Cd 0.07 lb Mg 0.5 lb Al-Ti master	46.1 lb high-purity Al 14.6 lb Al-Cu master 4.3 lb Al-Si master	46.1 lb high-purity Al 14.6 lb Al-Cu master 4.3 lb Al-Si master
Crucible	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2
Time Molten	45 min	45 min	35 min	50 min	40 min	35 min
Chlorine Fluxing Time	10 min	10 min	10 min	7 min	10 min	10 min
Chlorine Fluxing Temp	1310 to 1350 F	1440 to 1475 F	1450 to 1500 F	1400 to 1460 F	1445 to 1460 F	1450 to 1460 F
Maximum Melt Temp	1390 F	1475 F	1500 F	1460 F	1465 F	1460 F
Casting Temperature	1350 F	1400 F	1420 F	1300 F	1400 F	1405 F
Melt Additions						
Alloying Elements	4.5Cu(Al-Cu master) 0.25Mg	4.5Cu(Al-Cu master) 0.25Mg	4.5Cu(Al-Cu master) 0.1Cd 0.1Mg	4.5Cu(Al-Cu master) 0.1Cd 0.1Mg	4.5Cu(Al-Cu master) 0.8Si(Al-Si master)	4.5Cu(Al-Cu master) 0.8Si(Al-Si master)
Grain Refiners	0.1Ti(Al-Ti master)	0.1Ti(Al-Ti master)	0.05Ti(Al-Ti master)	0.05Ti(Al-Ti master)	None	None
Inoculant	None	None	None	None	None	None
Inhibitor	None	None	None	None	None	None
Moisture in Air	3.95 grains/ft^3	5.29 grains/ft^3	5.12 grains/ft^3	2.09 grains/ft^3	--	--
Molding Sand	(e)	(e)	(e)	(g) (i)	(e)	(e)
Permeability	100 to 120	100 to 120	100 to 120	85 to 120 105	105 to 140	125 to 140
Green Strength	0.8 to 1.2	0.8 to 1.2	0.8 to 1.2	0.6 to 1.5 2.5	0.6 to 1.2	0.6 to 1.2

TABLE A-1. (Continued)

	Melt 60	Melt 61	Melt 62	Melt 63	Melt 64	Melt 65
Purpose of Melt	High-purity 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	High-purity 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg	High-purity 195	High-purity 195	High-purity 4.5Cu-0.1Cd-0.1Mg-0.05Ti	High-purity 195
Melting Date	April 19, 1963	April 19, 1963	April 12, 1963	April 12, 1963	April 25, 1963	April 25, 1963
Alloy Charge	48.8 lb high-purity Al 14.6 lb Al-Cu master 1.3 lb Zn 0.06 lb Cd 0.06 lb Mg 0.16 lb Al-Cr master	48.8 lb high-purity Al 14.6 lb Al-Cu master 1.3 lb Zn 0.06 lb Cd 0.06 lb Mg 0.16 lb Al-Cr master	73 pounds of scrap from Heats 58 and 59	40 pounds of scrap from Heats 58, 59, and 62	42.3 lb high-purity Al 12.4 lb Al-Cu master 0.06 lb Cd 0.06 lb Mg 0.23 lb Al-Ti master	40 lb high-purity Al 12.4 lb Al-Cu master 3.7 lb Al-Si master
Crucible	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2
Time Molten	40 min	40 min	45 min	40 min	35 min	65 min
Chlorine Fluxing Time	8 min	8 min	10 min	5 min	8 min	8 min
Chlorine Fluxing Temp	1360 to 1380 F	1325 to 1385 F	1390 to 1475 F	1310 to 1430 F	1300 to 1390 F	1290 to 1410 F
Maximum Melt Temp	1390 F	1390 F	1475 F	1450 F	1400 F	1410 F
Casting Temperature	1330 F	1295 F	1370 & 1325 F(f)	1275 F	1340 F	1300 F
Melt Additions						
Alloying Elements	4.5Cu(Al-Cu master) 2.0Zn 0.1Cd 0.1Cr(Al-Cr master) 0.1Mg	4.5Cu(Al-Cu master) 2.0Zn 0.1Cd 0.1Cr(Al-Cr master) 0.1Mg	4.5Cu (in scrap) 0.8Si (in scrap)	4.5Cu (in scrap) 0.8Si (in scrap)	4.5Cu(Al-Cu master) 0.1Cd 0.1Mg	4.5Cu(Al-Cu master) 0.8Si(Al-Si master)
Grain Refiners	None	None	None	None	0.05Ti(Al-Ti master)	None
Inoculant	None	None	None	None	None	None
Inhibitor	None	None	None	None	None	None
Moisture in air	5.08 grains/ft^3	5.75 grains/ft^3	1.79 grains/ft^3	2.33 grains/ft^3	2.45 grains/ft^3	6.45 grains/ft^3
Molding Sand	(g) (j)	(g) (j)	(g) (h) (i)	(g) (i)	(g) (i) (j)	(g) (i) (j)
Permeability	135 to 150 105	135 to 150 105	85 to 120 110 105	85 to 120 105	120 to 260 105 105	120 to 260 105 105
Green Strength	0.75 2.8	0.75 2.8	0.6 to 1.5 0.6 2.5	0.6 to 1.5 2.5	0.4 to 1.0 2.5 2.8	0.4 to 1.0 2.5 2.8

TABLE A-1. (Continued)

	Melt 66	Melt 67	Melt 68	Melt 69
Purpose of Melt	High-purity 4.5Cu-0.25Mg-0.1Ti	High-purity 4.5Cu-0.25Mg-0.1Ti	High-purity 4.5Cu-0.1Cd-0.1Mg-0.05Ti	High-purity 4.5Cu-2.0Zn-0.1Cd-0.1Cr-0.1Mg
Melting Date	April 26, 1963	May 3, 1963	May 3, 1963	May 3, 1963
Alloy Charge	53.9 lb high-purity Al 15.8 lb Al-Cu master 0.18 lb Mg 1.17 lb Al-Ti master	65 lb of scrap from Heats 54, 55, and 66 plus 4.1 lb of high-purity Al(k)	50 lb of scrap from Heats 56, 57, and 64 plus 3.6 lb high-purity Al(k)	50 lb of scrap from Heats 60 and 61 plus 2 lb of high-purity Al(l)
Crucible	SiC No. 2	SiC No. 2	SiC No. 2	SiC No. 2
Time Molten	75 min	35 min	35 min	55 min
Chlorine Fluxing Time	8 min	7 min	7 min	9 min
Chlorine Fluxing Temp	1440 to 1480 F	1250 to 1370 F	1380 to 1480 F	1290 to 1390 F
Maximum Melt Temp	1480 F	1410 F	1480 F	1400 F
Casting Temperature	1350 F	1350 F	1350 F	1350 F
Melt Additions				
Alloying Elements	4.5Cu(Al-Cu master) 0.25 Mg	4.2Cu (in scrap) 0.33Mg (0.23 in scrap)	4.2Cu (in scrap) 0.14Mg (0.09 in scrap) 0.09Cd (in scrap)	4.3 Cu (in scrap) 1.9Zn (in scrap) 0.14Mg (0.09 in scrap) 0.09Cr (in scrap) 0.09Cd (in scrap)
Grain Refiners	0.1Ti(Al-Ti master)	0.09Ti (in scrap)	0.05Ti (in scrap)	None
Inoculant	None	None	None	None
Inhibitor	None	None	None	None
Moisture in Air	2.95 grains/ft^3	3.2 grains/ft^3	3.32 grains/ft^3	3.48 grains/ft^3
Molding Sand	(g) (h) (j)	(m)	(m)	(m)
Permeability	120 to 260 110 105			
Green Strength	0.4 to 1.0 0.6 2.8			

Footnotes for Table A-1

(a) 100 pounds of fine steel sand, 4 pounds of silica flour, 4 pints of water, 1 pint of oil, and 1/2 pint of kerosene. Baked 300 to 450 F for 7 hours. Sprayed with Lava wash and rebaked 1-1/2 hours at 400 F.
(b) Tensile bars recast September 10, 1962, using 39.1 pounds of scrap from Melt 20. Melt was chlorinated 10 minutes, held 10 minutes, and cast at 1405 F.
(c) Error in melt additions (0.1 pound magnesium instead of 1.05 pounds magnesium).
(d) Green sand used to prepare spiral molds (permeability 53, green strength 12.0).
(e) 100 pounds of fine steel sand, 4 pounds silica flour, 1.5 pounds corn flour, 4 pints water, 1 pint oil, 1/2 pint kerosene. Baked 2 hours at 300 F, 3 hours at 350 F, 1 hour at 400 F, and 1 hour at 450 F.
(f) Two castings at each temperature.
(g) Same as (e) except baking at 450 F omitted. Paraspray used to stop sand wash.
(h) 100 pounds of fine steel sand, 1.5 pounds of corn flour, 4 pints of water, 1/2 pint of oil, 1/2 pint of kerosene. Baked 1-1/2 hours at 350 F. (Used only for core of pump housing.) Paraspray used to stop sand wash.
(i) 100 pounds fine steel sand, 2-1/4 pounds of urea formaldehyde, 1 pound corn flour, 2 pounds Southern bentonite, 3 pints water, 85 cc ethylene glycol. Baked for 20 minutes at 320 F. (Used only for core of pump housing.) Paraspray used to stop sand wash.
(j) 70 pounds fine steel sand, 2-1/4 pounds urea formaldehyde, 3/4 pound corn meal, 1-1/2 pounds Southern bentonite, 2 pints water, 65 cc ethylene glycol. Baked 20 minutes at 320 F. (Used only for core of pump housing.) Paraspray used to stop sand wash.
(k) To reduce nominal copper content to 4.2 per cent.
(l) To reduce nominal copper content to 4.3 per cent.
(m) Sand data for these heats were lost. Procedures were similar to those used for Melts 64 through 66.

TABLE A-2. HIGH-PURITY ALUMINUM MASTER ALLOYS

Nominal Composition	Method of Preparation	Maximum Temperature, F	Alloy Addition	Composition by Analysis
Al-20Cu	Crucible melting (SiC)	1460-1600	OFHC copper	24.6Cu
		1445-1615	OFHC copper	17.3Cu
		1270-1600	OFHC copper	20.0Cu
		1280-1600	OFHC copper	19.9Cu
		1290-1600	OFHC copper	19.5Cu
Al-12Si	Crucible melting	1470-1525	Subsolar grade silicon	11.5Si
72Cu:28Ti	Arc melting	--		
72Cu:28Ti	Arc melting	--	OFHC copper Low-interstitial sponge titanium	--
Al-12.4Cu-4.8Ti	Crucible melting	1515-1760	72Cu:28Ti	Top: 12.4Cu:2.3Ti Bottom: 9.9Cu-8.3Ti
Al-14.5Mn	Arc melting	--	Manganese	--
Al-10Cr	Arc melting	--	Chromium	--
Al-5Cr	Arc melting	--	Chromium	--
Al-19.6Cu-0.4Be	Arc melting	--	Cu-2Be alloy	--

Note: All master alloys prepared with super-purity aluminum.

TABLE A-3. MATERIALS PURCHASED FOR PREPARING HIGH-PURITY ALLOYS

Description	Analysis
Super-purity aluminum	0.001Zn; 0.005Si; 0.001Fe; 0.001Zr; 0.002Ca; 0.000Mg, Cu, Ni, Ti, Cr, B, and Y
Al-50Fe	50.25Fe, 0.06Si, 0.10Mn, 0.04Cu
Al-6Ti master	6Ti nominal, <0.3Fe + Si by analysis
Cu	OFHC (99.99 per cent Cu)
Zn	Special high grade (99.99 per cent Zn)
Mg	High purity (99.8 per cent Mg)
Cd	Reagent grade
Cr	Iodide chromium
Mn	Electrolytic manganese
Ca	Reagent grade calcium
Cu-2Be alloy	1.8-2.05Be, 0.18-0.30Co
Si	Subsolar grade (99.99 per cent Si)

NASA-Langley, 1964

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OTS price, $2.25.
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